First demonstration of InGaP/InAlGaP based orange laser emitting at 608 nm

M.A. Majid, A.A. Al-Jabr, H.M. Oubei, M.S. Alias, D.H. Anjum, T.K. Ng and B.S. Ooi✉

The fabrication of orange-emitting semiconductor laser on interdiffused InGaP/InAlGaP structure is reported. The lasers lased at 22°C at a wavelength as short as 608 nm with threshold current density of 3.4 KAcm^{-2} and a maximum output power of ~46 mW. This is the shortest wavelength electrically pumped semiconductor laser emission from the InGaP/InAlGaP structure.

Introduction: Semiconductor visible laser diodes (LDs) cover a wide spectrum of wavelengths. For example, the InGaN/GaN based LDs cover the violet to green spectrum (~405–530 nm), and InGaP/InAlGaP system based LDs cover the red spectrum (635–690 nm). The wavelength from ~530–635 nm is not covered by any commercial LDs yet, which has some important applications in medicine [1, 2], horticulture [3], displays [4] and in optical communication using plastic fibres [5]. LDs in the green-yellow-orange range (530–635 nm) can be grown ideally either by InGaN/GaN or InGaP/InAlGaP based material system. For the InGaN/GaN quantum well (QW) structure, large strain and indium segregation prevent the growth of high quality light emitting devices in yellow and orange spectrum regions. In the case of the InGaP/InAlGaP system, small band offset between the QW and barriers leads small carrier confinement and large carrier leakage to prohibit the growth of high quality QW structures for yellow and orange emissions. The only access to orange, yellow and green regions has been achieved by frequency doubling of diode-pumped solid state lasers [6] or infrared LDs [7] or through the application of high external pressures which cause large blue-shifts of the emission wavelength of diode lasers [5]. However, the frequency doubled diode-pumped semiconductor lasers use non-linear crystals for inefficient second-harmonic generation and require externally distributed Bragg reflector and good heat sink, which makes the overall system more complex. Although InGaN based vertical-external-cavity surface-emitting lasers, also known as optically pumped semiconductor lasers, are worthy contenders for wavelength tuning, high optical output power and a nearly diffraction-limited beam quality means electrical pumping in these devices is challenging [8]. Moreover, the lasers produced by application of external pressure technique are non-practical for any commercial applications. Therefore, there is huge demand for replacements of these complex, expensive and power consuming lasers. In this letter we demonstrate the first room-temperature (RT) orange emission at 608 nm from the interdiffused InGaP/InAlGaP structure. Red laser (~640 nm) InGaP/InAlGaP structure is known to be very hard to have its bandgap blue-shifted using quantum well intermixing (QWI) technique [9]. Here, a novel QWI technique utilising strain-induced from a thick dielectric cap with cycles annealing at elevated temperature to promote interdiffusion. With this QWI technique, we have successfully tuned the bandgap of InGaP/InAlGaP structure from 640 to 565 nm.

Experiment: The single quantum well (SQW) InGaP/InAlGaP laser structure was grown on 10° offcut GaAs substrate using metal-organic chemical vapour deposition as shown in Fig. 1. The structure consists of a 200 nm Si-doped GaAs buffer layer with carrier concentration of 1-2 × 10^{18} cm^{-3}, 1 μm thick n-$In_{0.5}Al_{0.5}P$ lattice-matched lower cladding layer with carrier concentration of 1 × 10^{18} cm^{-3}, a SQW InGaP sandwiched between two 80 nm undoped $In_{0.5}Al_{0.3}Ga_{0.2}P$ waveguide layers, 1 μm thick Zn-doped $In_{0.5}Al_{0.5}P$ lattice-matched upper cladding with carrier concentration of 1 × 10^{18} cm^{-3}, 75 nm lattice matched p-$In_{0.5}Ga_{0.5}P$ barrier reduction layer with carrier concentration of 3 × 10^{18} cm^{-3} and 200 nm highly doped p-GaAs contact layer with carrier concentration of 2-3 × 10^{19} cm^{-3}. The emission of the laser was designed to be at 638 ± 2 nm.

For the novel QWI process, we studied the effect of the thickness of dielectric encapsulant (external strain), annealing temperature, annealing duration and number of cycles of annealing to identify the optimal process conditions for preserving the surface morphology, photoluminescence (PL) characteristics and electrical properties. For the purpose of this work a 1 μm thick SiO_2 cap, 950°C annealing temperature, five cycles of 30 s duration was applied to achieve the desired emission wavelength and optimal process conditions. The bandgap shifts induced by the above procedure were measured at RT using PL spectroscopy equipped with a 473 nm cobalt laser as the excitation source. Wafers were then processed using conventional processing and 1 mm long and 75 μm wide ridge devices were used for opto-electronic characterisation. All the devices were mounted on ceramic tiles and probed directly. The measurements were carried out at a tile temperature of 295 K, while pulsed operation (0.5 μs pulsed duration, 0.1% duty cycle) was used to minimise self-heating effects.

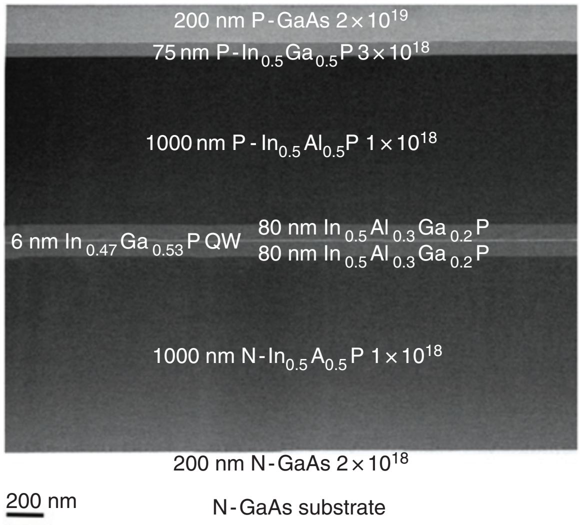


Fig. 1 *Dark field (002) cross-section TEM image of the InGaP/InAlGaP laser structure with an InGaP SQW*

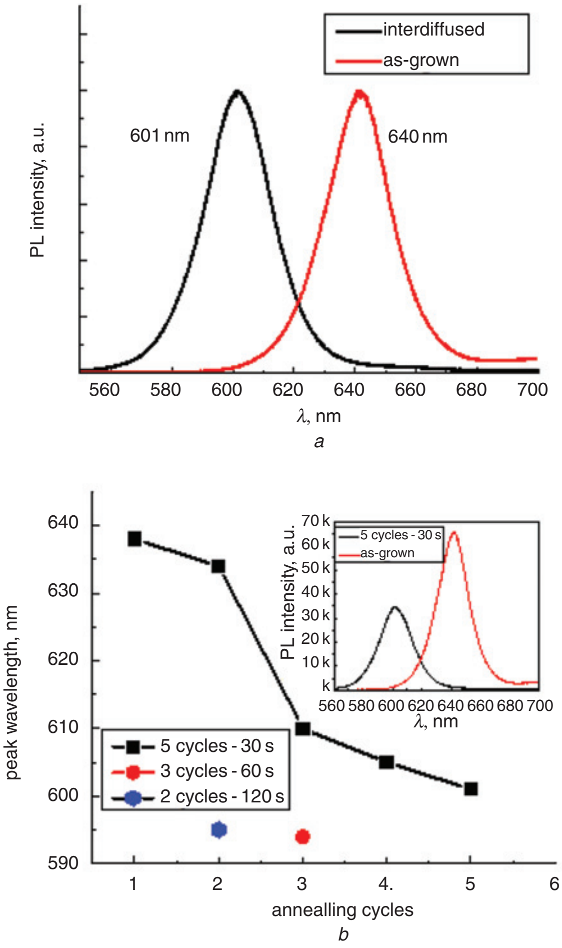
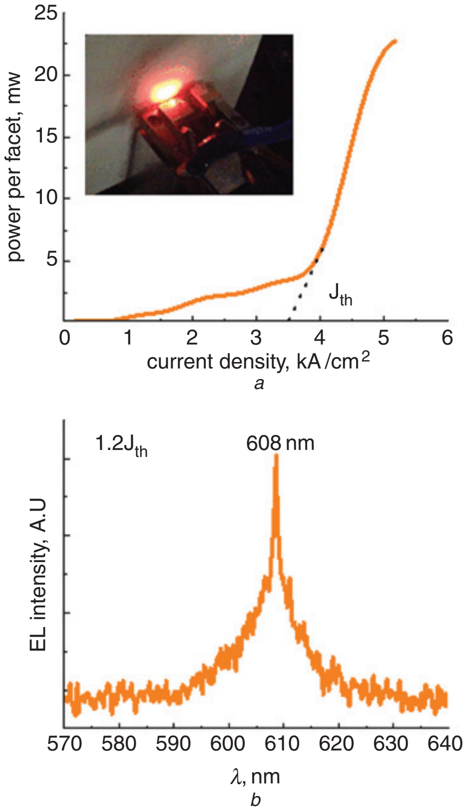


Fig. 2 *RT PL spectra of as-grown and novel QWI InGaP/InAlGaP sample after annealed at 950°C for five cycles of 30 s duration*

Results and discussion: Fig. 2*a* shows normalised RT PL spectra of as-grown and novel QWI InGaP/InAlGaP sample after annealing at 950°C for five cycles of 30 s duration. The degree of intermixing progressively increases with increasing number of annealing cycles. A bandgap blue-shift of 39 nm (~125 meV) was observed for the SiO_2 capped sample for 5 cycles of 30 s as shown in Fig. 2*b*. Similar bandgap blueshift is also observed for samples undergoing annealing for 3 cycles of 60 s and 2 cycles of 120 s as shown in Fig. 2*b*, but with a factor of ~4–5 times reduction in PL intensity while samples annealed for 5 cycles of 30 s maintained high PL intensity with factor of ~2 reduction in PL intensity (see inset Fig. 2*b*) with negligible increase in full-width at half maximum, which is important for subsequent fabrication of laser devices. In this material system we have obtained bandgap shift (not shown) of ~75 nm (250 meV) after 15 cycles of annealing for 30 s. This is the maximum bandgap shift in this material system at this short wavelength of ~640 nm.



a

b

Fig. 3 *Typical optical power-current characteristics of 1 mm long laser device and laser spectra*

a Power-current characteristics as a function of current density from 1 mm-long broad area laser fabricated from InGaP/InAlGaP interdiffused sample
Inset: orange lasing spot emitting at 608 nm
b RT lasing spectra obtained at a current injection of 1.2J_{th}

The significant bandgap blue-shift achieved here can be explained by the interaction of many factors. For such a large degree of intermixing, the driving force is postulated to originate from the combined effect of strain and vacancies induced interdiffusion to achieve strain relaxation during annealing. The SiO_2 has an expansion coefficient, ($\alpha = 0.5 \times 10^{-6}$ °C^{-1}), much lower than GaAs capping layer ($\alpha = 5.73 \times 10^{-6}$ °C^{-1}). This mismatch at the interface of the dielectric and semiconductor as well as the 1 µm thick SiO_2 induces compressive stress that facilitates the out-diffusion of Ga and formation of (group III) Ga vacancies. The Ga vacancies further accelerate the group-III out-diffusion process by providing the necessary migration energy for inter-diffusion [10].

Fig. 3*a* shows typical optical power-current characteristics of a 1 mm long laser device fabricated from a SiO_2 capped novel QWI sample. The inset shows the orange lasing spot at 1.2 times J_{th}. Fig. 3*b* shows the lasing spectra at a current injection of 1.2 times J_{th}. The laser exhibits lasing at 608 nm with a threshold current density (J_{th}) of 3.4 kAcm^{-2} and total output power of ~46 mW (two facets). It is to be noted that lasing emission red-shifted by ~7 nm as compared with PL emission, because of the leakage of injected current, particularly from the active region into the *p*-type cladding owing to the smaller conduction band offset. Researchers have observed orange emission at a low-temperature [11] or using external pressure at RT [5]. The as-grown sample of similar length, fabricated together with the intermixed sample, exhibited ~3 times less current density and ~6 times more output power at the lasing wavelength of ~640 nm. The increased current density and decreased output power is attributed to the increased optical losses owing to the diffusion of aluminium in the QW, strong and deleterious temperature effects due to the indirect minimum population and electron leakage because of smaller conduction band offset. Nevertheless, to the best of our knowledge, this is the first example of RT orange lasing emission yet reported from post-growth interdiffused process.

Conclusion: We have observed large bandgap shift in the InGaP/InAlGaP red laser structure with original lasing wavelength at 640 nm using novel strain-induced QWI technique. Orange lasers with peak lasing wavelenght at 608 nm and relatively good performance compared with the as-grown laser have been demonstrated in the interdiffused InGaP/InAlGaP structure.

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One or more of the Figures in this Letter are available in colour online.

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