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First Demonstration of Orange-yellow Light Emitter Devices in InGaP/ InAlGaP Laser Structure Using a Strain-induced Quantum Well Intermixing Technique

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Red to Yellow Semiconductor Emitters Based on Novel Strain-induced Inter-diffused InGaP/InAlGaP Structure Grown on GaAs

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***Abstract*: In this paper, a novel strain-induced quantum well intermixing (QWI) technique is employed on an InGaP/InAlGaP material system to promote interdiffusion via application of a thick-dielectric encapsulant layer, in conjunction with cycle annealing at elevated temperature. With this technique, we demonstrate the first yellow superluminescent (SLD) at a wavelength of 583nm with a total two-facet output power of ~4.5mW—the highest optical power ever reported at this wavelength in this material system. The demonstration of the yellow SLD without complicated multiquantum barriers to suppress the carrier overflow will have a great impact in realizing the yellow laser diode that cannot be grown with conventional methods.**

***Keywords*: InGaP/InAlGaP, orange & yellow emitters, lasers, strain, quantum-well intermixing, cycle annealing**

I. ACKNOWLEDGMENTS

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II. INTRODUCTION

Short wavelength high brightness visible semiconductor lasers have become increasingly important in numerous applications such as outdoor displays, solid state lighting, medicine, horticulture, and optical communication using plastic fibers[1]. These visible semiconductor lasers cover a wide spectrum of wavelengths. For example, the InGaN/GaN based commercial VSLs cover the violet to green spectrum (~405-530nm), and InGaP/InAlGaP visible semiconductor lasers are available in the wavelength range of 690-635nm. The wavelength from ~530-635nm (see Fig. 1) is not covered by any commercial visible semiconductor lasers yet, due to high leakage current in the InGaP/InAlGaP, and large strain and indium segregation prevent high quality emitters in the InGaN/GaN material system. The only access to the orange-yellow-green range has been achieved by application of high external pressures and low-temperature[2], frequency doubling of infrared lasers[3], or by frequency doubling of diode pumped solid state lasers[4]. In this paper, we demonstrate the first room-temperature (RT) high power (~4.5mW) yellow emitter from the interdiffused InGaP/InAlGaP structure grown on GaAs. The band gap of the short wavelength red laser's (~640nm) InGaP/InAlGaP structure is very difficult to blue-shift using the quantum well intermixing (QWI) technique[5]. Here, a novel strain-induced QWI technique was employed to promote interdiffusion via application of a thick dielectric encapsulant layer, with cycles annealing at elevated temperature. With this QWI technique, the bandgap of the InGaP/InAlGaP structure was successfully tuned from 640nm to 565nm (~250meV), and the first room-temperature orange laser was shown to have a decent output power of ~ 46mW at 608nm[1].

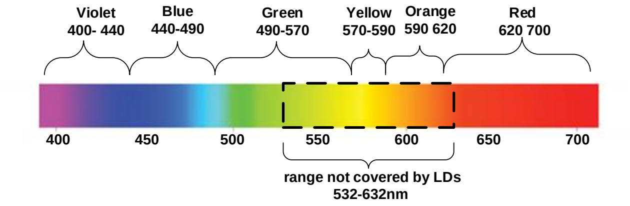

Fig.1 Range not covered by laser diodes

III. EXPERIMENT

The single quantum well (SQW) InGaP/InAlGaP laser structure was grown on 10° offcut GaAs substrate using metal-organic chemical vapor deposition (MOCVD) as shown in Fig. 2. The structure is described in detail elsewhere[1].The emission of the laser was designed to be at 638±2nm (see Fig. 3 (a) as-grown). For the novel QWI process, we studied the effect of the thickness (200nm-4000nm) of dielectric encapsulant (external strain), annealing temperature (700-1000°C), annealing duration (5-240s), and number of cycles of annealing (up to 23 cycles) to identify the optimal process conditions for preserving the surface morphology, photoluminescence (PL) characteristics, and electrical properties. For the purpose of this work a 1µm thick SiO_2 cap, 950°C annealing temperature, and cycles annealing of 30s duration were applied to achieve the desired emission wavelength and optimal process conditions. The bandgap shifts induced by the above procedure were measured at room-temperature (RT) using photoluminescence spectroscopy. Wafers were then processed using conventional processing, and 1mm long, 75µm wide ridge devices were used for opto-electronic characterization. All the devices were mounted on ceramic tiles and probed directly. The measurements were carried out at a tile temperature of 295K, while pulsed operation (0.5µs pulsed duration, 0.1% duty cycle) was used to minimize self-heating effects.

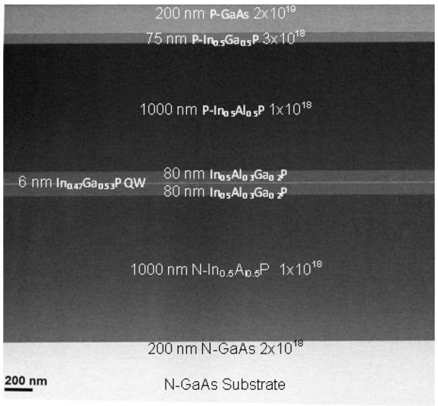

Fig. 2 Dark field (002) cross-section TEM image of the InGaP/InAlGaP laser structure with an InGaP SQW

IV. RESULTS AND DISCUSSION

Fig. 2 (a) shows normalized RT PL spectra of as-grown and novel QWI InGaP/InAlGaP samples after annealing at 950˚C for 5 and 9 cycles of 30s durations. A bandgap blue-shift of 39nm (~125meV) and 65nm (~220meV) was observed for 5 and 9 cycles of 30s. A similar bandgap blue-shift is also observed for samples which have undergone annealing for multiple cycles of 60, 90, 120, 180, and 240, but these were not considered in this study due to drastic reduction in PL intensity. The sample annealed for 5 cycles of 30s (601nm) maintained high PL intensity with a factor of ~1.5 reduction in PL intensity with a negligible increase in full-width at half maximum (FWHM). We demonstrated the first orange laser with a total power of ~46mW from this process.

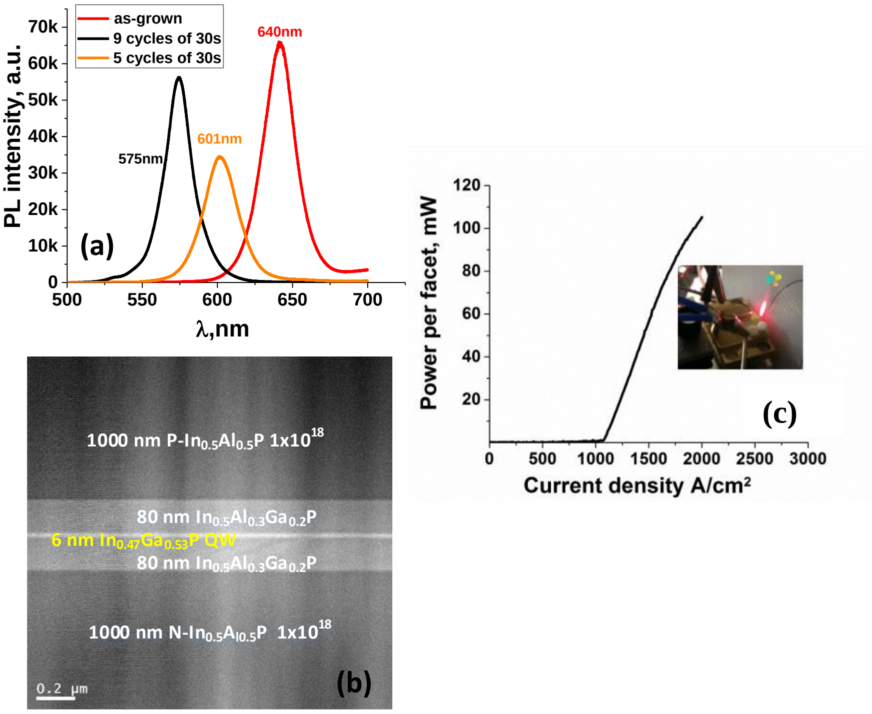

Fig. 3 (a) Room temperature PL spectra of as-grown and novel QWI InGaP/InAlGaP sample after annealed at 950˚C for 9 and 5 cycles of 30s duration, (b) Dark field (002) cross-section TEM image of the novel QWI sample for 9 cycles of annealing at 950˚C. (c) Power-current characteristics as a function of current density from 1mm long and 75µm wide broad area laser fabricated from InGaP/InAlGaP as grown. Inset: Red lasing spot emitting at a current injection of 1.2J_{th}.

The 9th cycle annealed sample (575nm) shows a negligible reduction in peak PL intensity, coupled with improved FWHM as compared to the as-grown sample (640nm), which is important for subsequent fabrication of laser devices. Fig 2 (a) shows the representative TEM micrograph for the samples annealed at 950C for 9 cycles of 30s. As can be seen from the figure, the composition at the interface of the quantum well (6nm-InGaP) and the barrier (80nm-InAlGaP) was abrupt like in the case of epitaxial growth samples. In fact, the HRTEM shows that the quantum well interface was sharper than noted in the as-grown sample, which explains the improved FWHM of this sample. The results clearly suggest that our novel strain-induced QWI technique is highly efficient for interdiffusion of composite atoms (Al/Ga) between a barrier and QW. By applying our novel QWI technique, we obtained a bandgap shift of ~75nm (250meV) after 15 cycles of annealing for 30s with ~6 times reduction in PL intensity as compared to as-grown. This is the maximum bandgap shift in this material system at this short wavelength of ~640nm. The reduction in peak PL intensity is not only due to degradation of the material quality, but also due to the reduced conduction band offset and high carrier leakage. We would like to point out that TEM images of the highly intermixed samples (PL @ 565nm) show good QW and barrier interface with negligible increase in quantum well width. This achievement may enable the prospect of a powerful and simplified fabrication route for optoelectronic device integration and low optical loss photonic integrated circuits based on the InGaP/InAlGaP material system. Furthermore, to compare the laser diode fabricated from the QWI technique, we have also shown the optical power-current characteristics of a 1mm long laser device, fabricated from an as-grown red laser, with electroluminescence at 1.2J_{th} (Fig. 3 (c)).

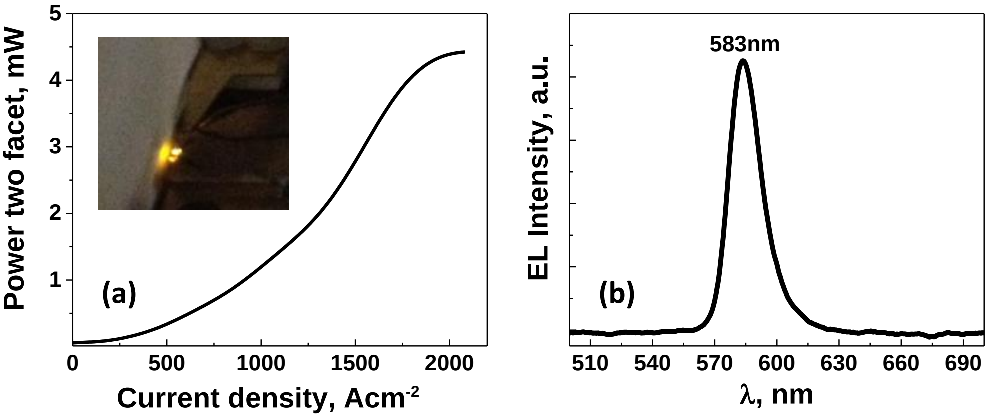

Fig. 4 (a) Power-current characteristics as a function of current density from 1.5mm long and 75µm wide broad area laser fabricated from InGaP/InAlGaP inter-diffused sample. Inset: yellow amplified spontaneous emission spot at 583nm, (b) amplified spontaneous emission spectra at 583nm.

Fig. 4 (a) shows typical optical power-current characteristics of a 1.5mm long and 75µm wide laser device at RT fabricated from 9 cycles of a novel QWI sample. The inset shows the yellow amplified spontaneous spot. Fig 3 (b) shows the 583nm amplified spontaneous emission spectra at a current density of 1500 A/cm^2. The laser devices exhibit a super-linear increase in optical power with increasing current density. We noted a 4.5mW total output power at a current density of 1750A/cm^2. This is the highest reported power at this wavelength on this material system at RT. The second best reported power was 0.36µW (two facets) on the strained–InGaP quantum well heterostructure grown on a transparent, compositionally graded AlInGaP buffer [6]. As a comparison, the orange laser lased around 3.4kAcm^{-2} at a total output power of ~46mW as shown in Fig. 5. Even through the yellow emitting device was 50% longer than the orange emitter, the power decreased by a factor of ~10 for only a 100 meV conduction band offset between both of the devices. The increased current density and decreased output power is attributed to the increased optical losses due to the diffusion of aluminium in the QW which was confirmed by a series of Electron Energy Loss Spectroscopy (EELS) combined with HRTEM (not shown), strong and deleterious temperature effects due to the indirect minimum population, and electron leakage due the smaller conduction band offset between AlInGaP and AlInP (in our case ~100meV). The results are very encouraging given that the cladding has no complicated multiquantum barrier (MQB) to suppress the carrier overflow. Probably the MQB will allow lower threshold and higher output power.

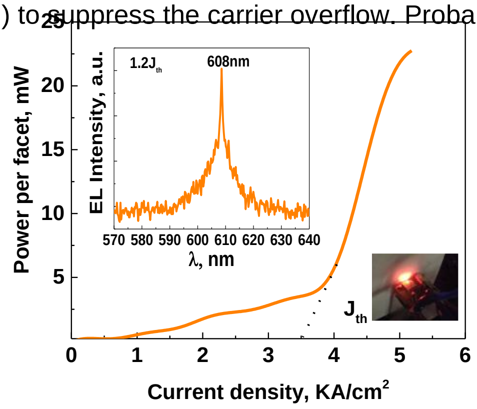

Fig. 5 Power-current characteristics as a function of current density from a 1mm long and 75µm wide broad area laser fabricated from an InGaP/InAlGaP inter-diffused sample. Inset: Orange lasing spot emitting at 608nm and RT lasing spectra obtained at a current injection of 1.2J$_{th}$.

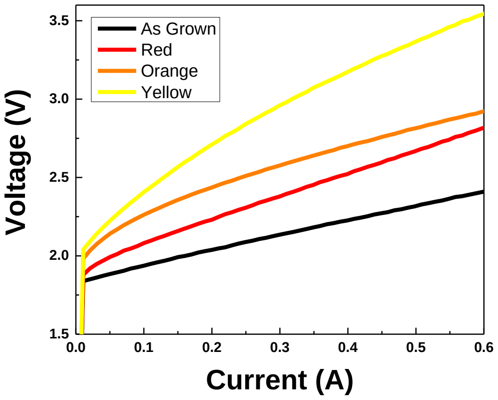

Fig. 6 Plot of the turn-on voltages of the intermixed laser structures compared to those of the as-grown structures

Fig. 6 shows the turn-on voltages of the intermixed emitter. The yellow emitter has a turn-on voltage of 2.1 V, which is approximately the bandgap of the device emitting at the operating wavelength of 585 nm. The emitter also has a low series resistance (<5 Ω). These good electrical characteristics for the yellow emitter with the highest degree of intermixing are evidence of the superiority of our intermixing process. In addition, the results confirm that the dopant concentration in the top contact and the cladding layers remained at a similar level and did not diffuse into the active region of the laser structure, even after the successive annealing at elevated temperatures.

V. CONCLUSION

We presented the visible semiconductor emitters using the novel strain-induced quantum-well intermixing technique on an InGaP/InAlGaP red laser structure. A maximum bandgap shift of ~250meV with an original wavelength of 645nm is observed in this material system. An orange laser and a yellow emitter with a peak wavelength at 608nm and 583nm with relatively good performance have been demonstrated at room temperature**.** The novel technique presented in this article may represent a solution for producing high-efficiency AlGaInP devices at the shorter wavelengths of yellow and orange colors, and it has potential application for producing passive sections, e.g., the non-absorbing window, in the InGaP/InAlGaP material system.

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