Epitaxial growth of AlInGaAs/InP for high temperature operation of photonic integrated lasers at 1550 nm

A. Kapoor,[1,2] J. Hazan,[2] and V. Dolores-Calzadilla[1,2]

[1] Photonic Integration Technology Center (PITC), Groene Loper 19, 5612 AP Eindhoven, The Netherlands

[2] Department of Electrical Engineering and Eindhoven Hendrik Casimir Institute, Eindhoven University of Technology, Groene Loper 19, 5612 AP Eindhoven, The Netherlands

Highly reliable lasers operating at elevated temperatures are attractive for a number of uncooled applications. The AlInGaAs material system has been reported to be suitable for such lasers in the past [1,2]. However, well controlled growth of this alloy with various strained compositions still remains a challenge. This work presents the growth of both lattice matched and strained AlInGaAs on InP using a state of the art As/P metal organic chemical vapor phase deposition (MOCVD) planetary reactor. A detailed investigation combining photoluminescence (PL) and X-ray diffraction (XRD) is presented to fully understand the bandgap tuning with aluminum composition. The study is applied to multiple quantum wells (MQWs) stack for laser diodes emitting at 1550 nm, for which simulations predict robust electro-optical performance up to 80 ˚C as compared to standard layerstacks based on InGaAsP-MQWs.

Introduction

In integrated photonics, where bandgap versatility is exploited, different material systems are used for the implementation of modulators, semiconductor optical amplifiers and lasers. The quaternary semiconductor systems InGaAsP (P-Q) and AlInGaAs (Al-Q) are of great importance as their bandgap can be tunned to cover several spectral bands highly relevant for optical communications (e.g. C-band for long-haul telecommunications and O-band for datacenters). Both materials are widely used commercially, however Al-Q alloy is of particular interest as it has demonstrated improved performances at higher temperature operations [1, 2]. The Al-Q alloy has a larger conduction band offset ($\Delta E_c/\Delta E_g$=0.7) compared to P-Q ($\Delta E_c/\Delta E_g$=0.4) thus resulting in better electron confinement [3].

A reduction in threshold current density (J_{th}) for Al-QWs compared to P-QWs lasers emitting at 1550 nm has been reported in theoretical work. [1] This is observed for both varying compressive strain (0.0 – 1.5 %) as well as varying operating temperature (30 – 126 ˚C). Similarly, a buried tunnel junction (BTJ) based on InGaAs/AlInGaAs superlattice demonstrates a stable single-mode lasing with threshold current < 1.3 mA and output optical power > 6 mW and operation in a wide temperature range (up to 85 ˚C) [4]. Another work describes that an Al-Q based electro-absorption modulator (EAM) with distributed feedback laser diode is suitable as a 10- and 40-Gb/s uncooled light source. The authors report an extinction ratio of over 9 dB from -25 ˚C to 100 ˚C for 10-Gb/s operation and 8.2 dB from -15 ˚C to 80 ˚C for 40-Gb/s operation [2].

The above reports present explicit device-level improvements, however these advantages of the Al-Q system are not yet incorporated into InP-based photonic integrated circuits (PICs) [5]. Current commercially available InP based PICs rely on P-Q and are reaching maturity. The Al-Q system represents the next generation of InP PIC technology suitable for high-operating temperatures, high integration density of components, and heterogeneous integration of InP onto different substrates, where increased thermal resistance is expected to be an issue.

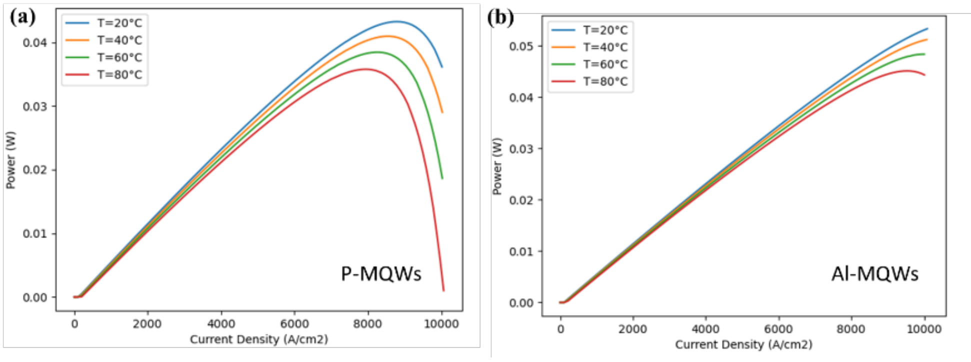

Fig. 1. Simulated results on Fabry-Perot laser power at different operating temperatures (20 – 80 ˚C) for (a) Standard P-based laser and (b) New proposed Al-based laser layerstack design. Thermal roll-off is only observed for the P-based MQW laser device.

In order to understand the potential performance of laser devices relying on Al-Q layerstacks, we first carried out simulations of Fabry Perot laser cavities (length = 4.5 mm, waveguide width 2µm). In Fig. 1, the electro-optical performance of such laser devices is compared by measuring the optical output power for different temperatures (20, 40, 60 and 80 ˚C). The target MQW layerstack is based on AlInGaAs QW/QBs, whereas the reference MQW layerstack is based on InGaAsP QW/QBs. The number of QW/QB remains the same. As it can be observed, a more robust electro-optical performance (i.e. without thermal roll-off) can be observed for the Fabry Perot laser with Al-based MQW gain medium, when compared to P-based MQWs stack. Further performance of the designed lasers is out of the scope of this paper. The work then focuses on the epitaxial growth of Al-Q bulk on InP substrates. The growth conditions are carefully monitored to establish both lattice matched and strained Al-Q. The work is further extended to prepare Al-MQWs stack for laser emission at 1550 nm.

Experiments & Results

The bandgap engineering of Al-Q is mainly achieved by tuning the aluminum content between $In_{0.53}Ga_{0.47}As$ (0.76 eV) and $In_{0.52}Al_{0.48}As$ (1.46 eV). A state of the art As/P G10 MOCVD planetary reactor by AIXTRON is used to prepare the samples. This next gen-reactor has a 12 x 4” susceptor design and has an automated wafer handler for particle control. Samples of bulk $Al_xIn_{(1-x-y)}Ga_yAs$ sandwiched between InP buffer and a cap with varying Al-composition (x) are grown on 4” semi-insulating (Fe-doped) InP wafer as depicted in Fig. 2(a). The group III elements are introduced using trimethylaluminum (TMAl), trimethylgallium (TMGa) and trimethylindium (TMIn) as precursors, while for group V elements, hydrides namely arsine and phosphine are used. The growth temperature is 615 ˚C for all wafers, thanks to in-situ EpiTT that monitors the real time surface temperature on the wafer. A standard growth pressure of 600 mbar is used for InP and increased to 1200 mbar for Al-Q growth. Once the epitaxy conditions were tuned to grow bulk AlInGaAs at 1550nm, the work was further extended to grow MQWs layerstacks as shown in Fig. 2(b) usingsimilar growth conditions as mentioned above. The stack includes several pairs of AlInGaAs quantum wells (QWs) to target 1550 nm separated by AlInGaAs quantum barriers (QBs).

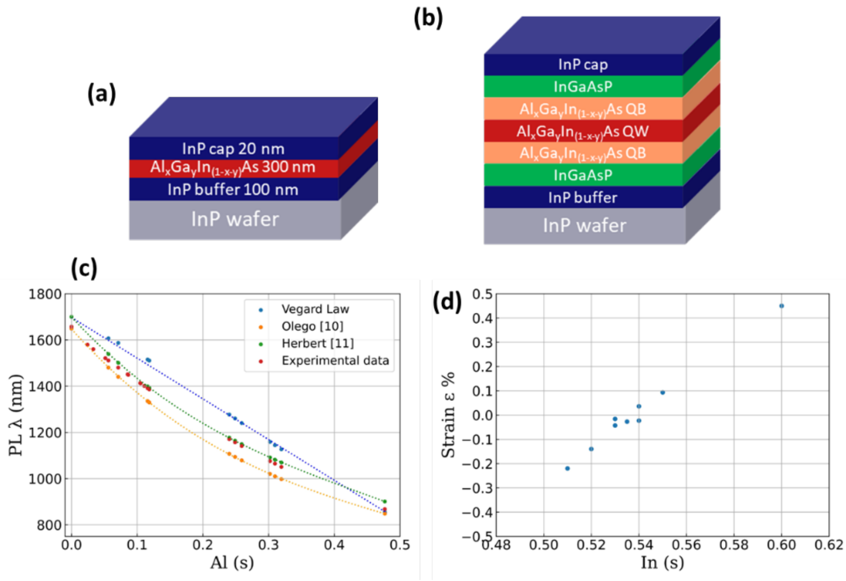

Fig. 2. Schematics of layerstack containing (a) bulk AlInGaAs and (b) AlInGaAs/AlInGaAs MQWs; (c) PL peak wavelength vs solid phase Al-fraction for bulk AlInGaAs, (d) Measured strain ϵ% vs solid phase In-fraction in AlInGaAs

The optical characterization of all wafers is performed using room temperature photoluminescence (RT-PL) by exciting with a 532 nm laser with 5mW optical power. The measured PL emission at different Al-compositions is seen in Fig. 2(c) for bulk Al-Q. The bandgap bowing compared to Vegard's law has also been observed in literature [6][7][8] and generally associated with alloy disorder [9] or difference in growth conditions [10]. The experimental data is in close agreement with the bandgap interpolation reported in [7]. The lattice mismatch, and QWs properties are measured using high resolution X-ray diffraction (HR-XRD). The influence of changing In-composition on strain can be seen in Fig. 2(d). Clearly for lattice matched composition i.e. In (s) = 0.53 and (Ga + Al) = 0.47, the resulting strain $\epsilon = 0$. For increasing indium i.e. less gallium the alloy has compressive strain ($\epsilon > 0\%$) while for decreasing indium i.e more gallium, the alloy has tensile strain ($\epsilon < 0\%$).

The PL and strain dependence on Al- and In-composition respectively is then utilized to grow a MQWs stack for laser emitting at 1550 nm. A full wafer map of PL emission (λ) in the left of Fig. 3. shows the average PL emission at 1548 nm with an excellent uniformity (σ ≈ 1 nm). The right side shows a PL spectra for a single point on the wafer emitting at 1549 nm with an appreciable PL intensity of 2.7 V and full-with half-maximum of 72nm. The wafer is further investigated by HR-XRD measurement. The standard rocking curve was fitted to deduce the QWs and QBs' thicknesses, whose composition and strain were verified to be 4.8% of Al-content and 0.94% compressive strain in QWs while -0.54% tensile strain in barriers..

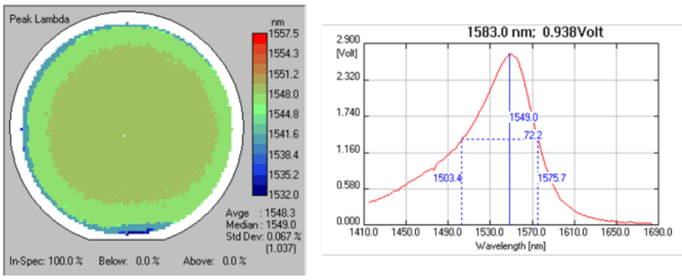

Fig. 3. Left shows full 4" wafer map for PL emission with 5 mm exclusion zone, right - shows the single point PL spectra at 1549 nm.

Conclusions

This work demonstrates the growth of AlInGaAs alloy both in bulk and MQW design in 4” substrates for their use in the next-generation of integrated photonics platforms. A detailed understanding for growth conditions is presented combined with a comprehensive wafer characterization using PL and XRD.

Acknowledgements

The authors would like to acknowledge AIXTRON for the continuous cooperation, and the PhotonDelta National Growth Fund program targeting the industrialization of integrated photonics.

References

[1] S.H. Park, “High Temperature Characteristics of Strained InGaAs/InGaAlAs Quantum Well Lasers”, Jpn. J. Appl. Phys., vol. 36, 3528-3530, 1997.

[2] W. Kobayashi, M. Arai, T. Yamanaka, N. Fujiwara, T. Fujisawa, T. Tadokoro, K. Tsuzuki, Y. Kondo, and F. Kano, “Design and fabrication of 10-/40-Gb/s, uncooled electroabsorption modulator integrated DFB laser with butt-joint structure”, Journal of Lightwave Technology, vol. 28, 164-171, 2010.

[3] T. Ishikawa, “Band lineup and in-plane effective mass of InGaAsP or InGaAlAs on InP strained-layer quantum well”, J. Quantum Electron, vol. 30, 562–570, 1994.

[4] S. A. Blokhin, A.V. Babichev, A.G. Gladyshev, L.Y. Karachinsky et al.,“High Power Single Mode 1300-nm Superlattice Based VCSEL: Impact of the Buried Tunnel Junction Diameter on Performance”, IEEE Journal of quantum electronics, vol. 58, 1-15, 2022.

[5] M. Smit et al., “An introduction to InP-based generic integration technology”, Semicond. Sci. Technology, vol. 29, 083001, 2014

[6] D. Olego, T. Y. Chang, E. Silberg, E. A. Caridi and A. Pinczuk, “Compositional dependence of band-gap energy and conduction-band effective mass of $In_{(1-x-y)}$ Ga_xAl_yAs lattice matched to InP”, Appl. Phys. Letter, vol. 41, 476–478, 1982.

[7] E. Herbert Li, “Material parameters of InGaAsP and InAlGaAs systems for use in quantum well structures at low and room temperatures”, Physica E: Low-Dimensional Systems and Nanostructures, vol. 5, 215–273, 2000.

[8] J. Böhrer, A. Krost and D. B. Bimberg, “Composition dependence of band gap and type of lineup in $In_{1-x-y}Ga_xAl_yAs$/InP heterostructures”, Appl. Phys. Lett., vol. 63, 1918–1920, 1993.

[9] J. A. van Vechten and T. K. Beergstresser, “Electronic structure of semiconductor alloy”, Phys. Rev. B, vol. 1, 3351, 1970.

[10] M. Zyskowski, N. de Louw, S. Kleijn and F. J. D. Otero, “Strained AlGaInAs on InP: Bandgap dependence on composition—Model benchmark and optimization”, J. Appl. Phys., vol. 134, 243103, 2023.