AlInGaAs MQW laser layerstacks for the InP generic integration platform

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We designed a series of AlInGaAs MQW laser layerstacks in order to investigate the influence of various design parameters (such as amount of quantum wells, doping strategy, SCH profile) on the laser performance. The stacks are experimentally evaluated by fabricating and testing Broad Area Lasers. Their design is optimized for automated measurement and rapid prototyping allowing for collecting large amounts of data. This enables statistically significant comparison between various Al-based layerstacks and with an InGaAsP reference layerstack (currently used in Smart Photonics generic platform), making the comparisons more reliable than in the existing literature.
The Al-based MQW lasers show significantly improved performance, at 70 °C, paving the way towards adoption of AlInGaAs gain section in Smart Photonics generic integration technology enabling better high temperature performance.

Introduction

Global data-based economy demands more datacenters as more services require cloud computing and big data infrastructure. Such demand goes hand-in-hand with large energy consumption.[1] Conventional InGaAsP lasers used in optical fiber communications have low efficiency at high temperature, requiring external cooling and consuming large amount of energy.[2] This is not only economically inefficient but also unsustainable from the ecological point of view. To remediate this problem, it is important to develop lasers that perform well in the high-temperature environment of a datacenter without the need for cooling. First step on that path is to develop suitable gain material.
Gain material's performance at given temperature can be described by three metrics: Threshold current density at transparency (J_{transp}), internal quantum efficiency (η_{in}), and internal loss. Robustness of the first two metrics against temperature is characterized by characteristic temperatures T0 and T1 respectively. They can be derived from the equations 1:

$$J_{transp} = Je^{\frac{T}{T0}} \qquad 1$$

$$\eta_{in} = \eta e^{-\frac{T}{T1}}$$

AlInGaAs is a very promising material for quantum wells-based gain section because conduction band offset of this alloy is 0.7, meaning that a quantum well created with this material is "deeper" compared to, for example, conventionally used InGaAsP, which has conduction band offset of just 0.4.[3] This allows for better confinement of the electrons and lower leakage current, which is particularly important at higher temperatures.
In our study, except for testing the influence of amount of AlInGaAs quantum wells, we also have tested the impact of three different types of Separate Confinement Heterostructures (SCH), namely the standard SCH, Graded Index SCH (GRINSCH), and SCH with aggressive doping scheme (as pictured on fig 1).

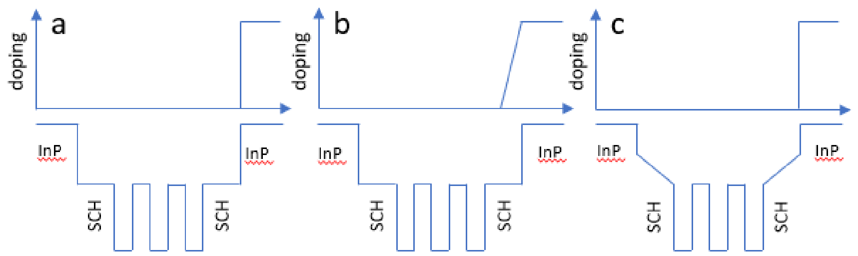

Figure 1. (a) Typical SCH structure, (b) Structure with aggressive doping profile, (c) GRINSCH type of structure.

While previous studies have already investigated AlInGaAs layerstacks, to our best knowledge all of them tested small number of lasers, meaning that their results could've been strongly influenced by randomness caused by the fabrication process. Using the opportunity given by mass-production capabilities of SMART photonics, we have manufactured and characterized hundreds of Broad Area Lasers (BALs), allowing for statistically solid comparison.

Experiment

We used MOVPE technique to grow the layerstacks on (100) InP n-doped wafers. Subsequently we transferred a pattern of BALs onto them using standard lithographic process. BALs used for our study had cavity width of 50 µm and lengths of 500, 1000, 1500 and 2000 µm. To automatically characterize the BALs, we used bar tester made of Wentworth Pegasus S200 wafer prober and Keithley 2520 Source-Meter Unit, and Thorlabs' Optical Spectrum Analyzer 203C, with custom controlling elements and thermostatic system.
From the center of each wafer, we cleaved-out bars, each containing up to 20 BALs of given cavity length (one cavity length per bar). The automated test was carried out at 20, 40, and 70 degrees Celsius, using pulsed current mode (pulse width 5 µs, duty cycle 1%). In processing of the LIV curves, we took into account that optical power measurement took place only at one facet. Current sweep was up to 10kA/cm^2, or to the SMU's limit of 5A in steps of 1mA. For the derivation of J_{transp}, η_{in} and loss, we have selected several best-performing lasers of given length, knowing that at that stage of development it is possible to create some underperforming lasers. This low number of samples explains large uncertainties of measurements. Parameters were obtained using methods described in [4]. To measure wall-plug efficiency we divided optical power emitted from one facet by the current multiplied by voltage, as measured by the bar tester. In this case, while absolute values are 50% lower than real, it doesn't matter, since here we use relative values only.

Results and discussion

In figure 2 one can see the results of our measurements. The corresponding T0 and T1 parameters are shown in table 1. We also present relative average maximum wall-plug efficiencies (η_{WP}) at various temperatures for the 1.5 mm long devices, normalized to the reference devices' performance at given temperature.

Wafer	T0 (K)	T1 (K)	η_{WP} at 20C	η_{WP} at 40C	η_{WP} at 70C
38, 3QW	71	59	160%	171%	231%
36, 4QW+doped SCH	83	95	117%	118%	147%
50, 4QW+GRINSCH	83	59	141%	137%	136%
Current MPW P stack	73	56	100%	100%	100%

Table 1. Thermal characteristics and relative wall plug efficiency of BALs investigated in the study.

It comes as no surprise that AlInGaAs BALs significantly outperform the InGaAsP devices, especially at higher temperatures. To our best knowledge, there are no other studies of η_{WP} of AlInGaAs BALs emitting at 1500 nm, therefore it is impossible to relate our results to those of other researchers.
T0 of samples 36 and 50 is comparable with Tandon (80K)[5] and better than Liu (55K).[6] In terms of T1 improvement, sample 36 performs particularly well. We attribute it to increased confinement potential caused by doping, as predicted by Tandon.[5]. While doping inside of SCH makes the sample 36 most lossy of our Al-based stacks, as seen in figure 2, it is still less lossy than the reference layerstack.
Sample 38 has the smallest losses. It has been shown by Tandon that decreasing amount of QWs decreases losses not only in AlInGaAs but also in InGaAsP.
Reference layerstack has 4 QWs, therefore it is clear, that AlInGaAs lasers have better transparency current density per QW even at room temperature. This may be result of not only different material system, but also higher strain in the QWs, considering that the width of quantum wells is almost the same in all cases.[7]
Internal quantum efficiency is comparable for all the layerstacks, except for the sample 36, which significantly stands out at 70 °C. While IQE appears comparable, clear AlInGaAs superiority can be established from η_{WP} that can be seen in table 1.
In figure 3 one can see the maximal power comparison of our wafers. Maximal power of AlInGaAs devices can be almost twice as large as the one of reference lasers.

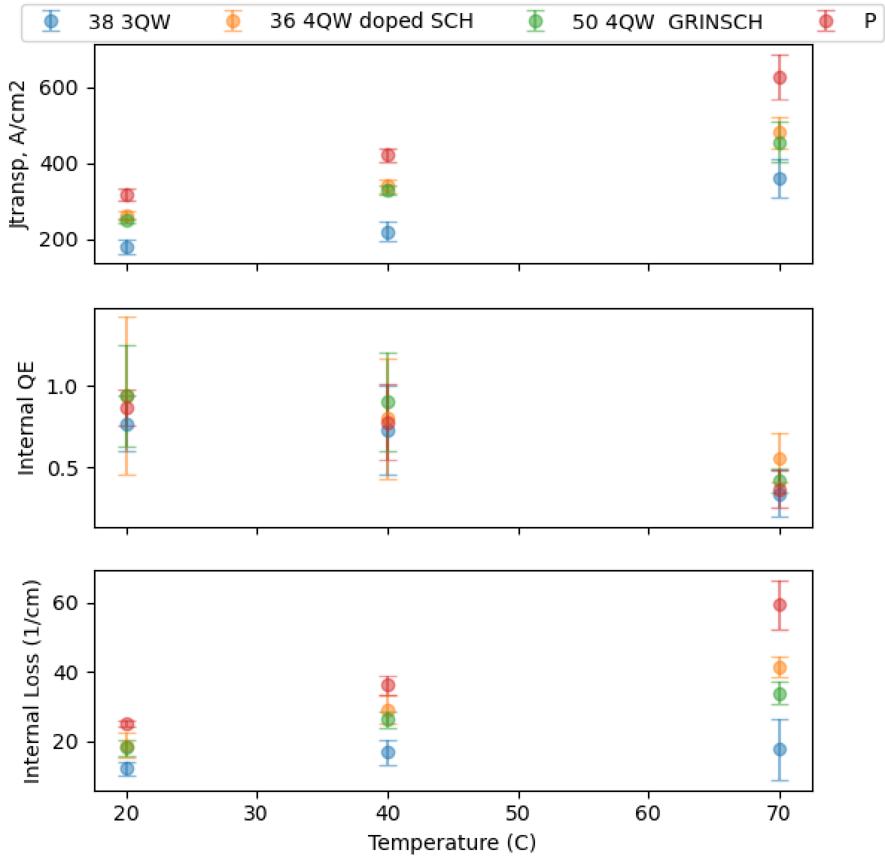

Figure 2. Results of BAL performance investigation.

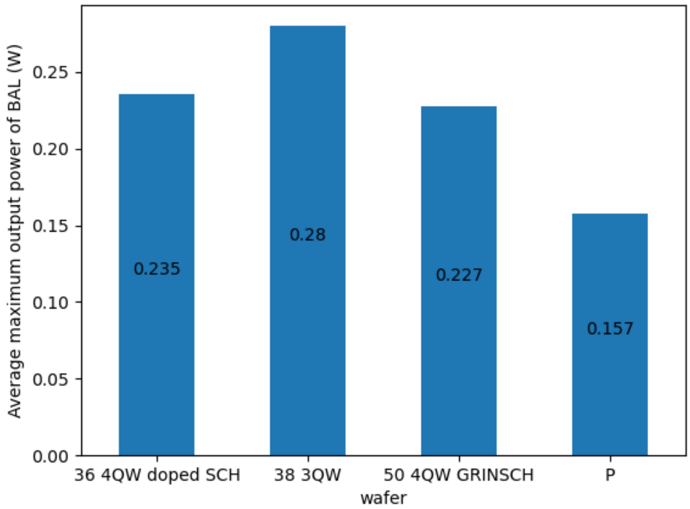

Figure 3. Average maximum output power of BALs as a function of layerstack design for 1-mm BALs at 70°C (only best 60 percentiles of BALs from each wafer considered here)

Conclusion

In our research we managed to develop lasers that are clearly superior to the existing platform and obtained useful information helpful in perfecting them even further. For example, it would be highly desirable to obtain a gain medium with high T1 and low threshold current and low losses by growing a layerstack with three quantum wells and doped SCH. There are also other techniques for T1 enhancement to explore, such as asymmetric SCH or inclusion of electron-stopping layer in the layerstack.

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