Development of near UV laser diodes

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***Abstract* — The development of near ultraviolet laser diodes based on the AlGaN materials system on single crystal GaN substrates is presented. This includes growth of relaxed Ga-rich AlGaN layers, design of UV laser diodes, as well as discussion of the electrical and optical properties. We show that with the demonstration of optically pumped lasers, a pathway toward electrically injected laser diodes is available.**

Keywords—UV laser, AlGaN, optically pumped.

I. INTRODUCTION

III-Nitride based near UV laser diodes (near UV = 300 - 400 nm) have been under investigation since the discovery of p-conductivity in GaN (1). However, most work was focused on the wavelength >370 nm for applications in solid state lighting, optical data storage, and sensing. In contrast, only very limited data is available for LEDs and lasers with emission between 300 – 350 nm. However, optoelectronic devices emitting in this wavelength range are expected to find many applications including treatment of vitamin D deficiency, UV sensing, materials processing, and others (2, 3). Challenges for sub 350 nm optoelectronic devices based on the AlGaN materials system include: (a) growth of Indium-free active regions; (b) design of structures that can tolerate an absorbing p-contact layer (bandgap of the typically used top p-layer is around 350 nm); (c) design of efficient wave guides, doping of AlGaN cladding layers and design of efficient carrier confinement schemes; (d) control of high dislocation densities to achieve best radiative recombination rates, and growth of high quality AlGaN layers. Most of these challenges can be addressed by growing AlGaN epitaxial layers via metal-organic chemical vapor deposition on single crystal GaN or AlN substrates. Using such single crystal substrates best layer qualities can be achieved with dislocation densities in the 10^3 - 10^5 cm^{-2} range which allows for lowest UV laser thresholds and highest IQE (4-6).

In this work, we present a comprehensive study describing work that will lead to low threshold near UV laser diodes. We describe growth of Ga-rich AlGaN layers and MQWs on GaN substrates and related relaxation efforts. Furthermore we will shortly discuss optically pumped near UV lasing and the optical and electrical properties of electrically injected devices. In summary, this will highlight the pathway to achieve electrically injected lasing in the near UV.

II. EXPERIMENTAL

Ga-rich AlGaN layers were grown using low-pressure metalorganic chemical vapor deposition (LP-MOCVD). Trimethylaluminum (TMA), triethylgallium (TEG), and ammonia (NH_3) were used as sources for Al, Ga, and N, respectively. Details on the growth process and substrate preparation can be found elsewhere (7). Structures were typically grown on single crystal GaN substrates grown by the ammonothermal method. Dislocation densities in these substrates are in the 10^3 cm^{-2} range which allows for highest crystal quality and well defined active regions (8).

Structures were optically characterized using photoluminescence spectroscopy and UV laser threshold measurement and characterized electrically by recording I-V and I-L curves (9).

III. RESULTS AND DISCUSSION

In order to investigate the potential of low dislocation density substrates, optically pumped laser structures were investigated first. Figure 1 (left) shows the emission spectra of a single quantum well designed for the near UV range, embedded in an Al-rich (70% Al-content) waveguide as recorded from the facet of the device. In addition, in Figure 1 (right) the light emission intensity as a function of the excitation power density is shown. The main emission peak of the device is found around 325 - 330 nm. Initially, at low excitation power densities, the emission is relatively broad and shows a linear increase of the integral intensity with the pumping power. For pumping power densities around 800 kW/cm^2 a sudden non-linear increase is observed. This behavior is typical for a laser below and above the laser threshold. Based on an analysis of Figure 1 (right) a laser threshold of 850 kW/cm^2 is estimated. This value is significantly higher than the threshold of previously discussed

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UV-C laser diodes on low dislocation substrates ($\approx$5 kW/cm^2) (6, 10) but comparable to other works on sapphire (11). However, it is pointed out that the previous low threshold lasers were multi quantum well structures with higher IQE and that the present near UV laser structures investigated in Figure 1 have a wide active region (10 nm from TEM). Thus, lower optically pumped laser threshold are expected in advanced laser designs using optimized active regions. Finally it should be mentioned that gain measurements in these and other structures were performed and an achievable modal peak gain of 40-80 cm^{-1} was measured which is comparable to results from InGaN based blue lasers (9, 12).

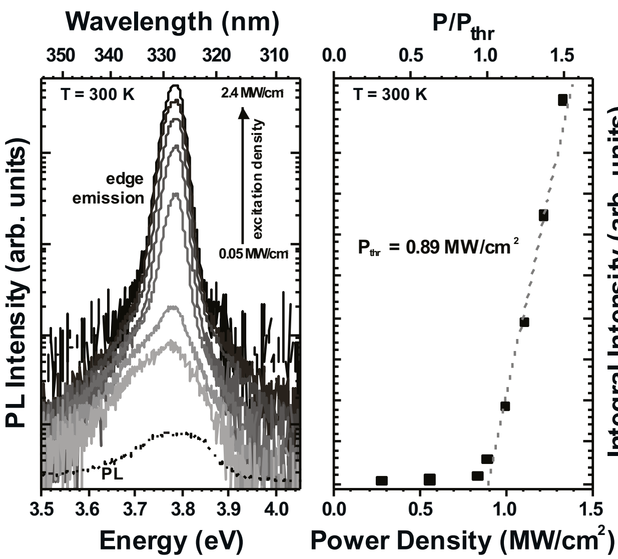

Figure 1: (left) Emission spectra of the laser structure recorded from a cleaved edge depending on the excitation power density. A significant, non-linear increase of the intensity is observed indicating lasing. (right) Analysis of the integral intensity depending on the excitation power density. A strong increase of the intensity for pumping power above the laser threshold of around 800 kW/ cm^2 is observed.

Finally, full laser structures for near UV emission around 340 nm were designed using SILVACO simulation software. In general, favorable structures were found to be comparable to those desired for visible and mid-UV laser diodes (13-15). One particular challenge for growth of Ga-rich AlGaN layers is the implementation of appropriate relaxation schemes. This is because AlGaN growth under tensile strain on GaN results in catastrophic cracking and prevents the growth and fabrication of laser diodes. We therefore employed FACELO which has been shown to result in relaxed AlGaN layers (16). In this process, first a thin SiO_2 layer is deposited on the Ammono GaN substrate. Then the oxide film is patterned using photoresist and RIE etching leading to 2 µm wide openings. In the second step a GaN:Si layer is grown on such a prepared substrate using MOCVD and under growth conditions that suppress significant lateral growth resulting in GaN stripes with triangular cross-section. Finally Ga-rich AlGaN (Al-content 20-30%) is grown on these GaN templates. The main challenge is to achieve coalescence of the AlGaN films. This is achieved by growing under growth conditions that favors a significant lateral growth rate. After a fully coalesced AlGaN film is grown, the UV laser diode structure with cladding layer, waveguides, and active region is grown on top of the relaxed AlGaN. A SEM image of the grown structure including the FACELO template is shown in Figure 2 (left) with a magnified image highlighting the actual laser diode in Figure 2 (right). The cladding layer and the waveguide are clearly identified and the thicknesses are close to the intentional thickness of 500 nm (cladding layers) and 100 nm (waveguide). The MQW is not seen because of the limited resolution of SEM, but TEM was done to confirm quality of the active region as well. Despite the underlying n-AlGaN template and the GaN pyramids used for relaxation, the interfaces of the different layers are found to be well defined and the layers were homogenous. Using optical microscopy, no cracking of the device was observed and the surface looked smooth and free of major defects, confirming that the chosen relaxation scheme can lead to electrically addressable UV laser diodes.

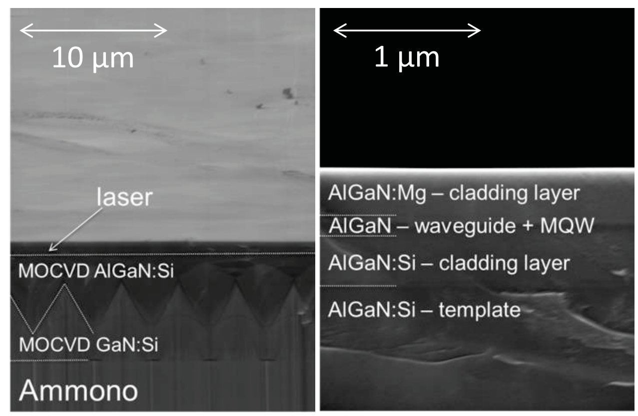

Figure 2: (left) SEM photograph of a laser diode structure grown on Ammono GaN substrate. The image includes the relaxed GaN/AlGaN layer and the laser diode. (right) Close-up of the laser diodes with the cladding layers and waveguide visible.

The epitaxially grown laser diodes were fabricated using standard photolithography in combination with RIE etching. P- and n-contacts were deposited on the front side (p-GaN) and back side (n-GaN substrate) of the devices making the fabricated laser diodes vertical devices (17-19). Single laser diodes with injection width/p-contact width of 5 µm were separated by SiO_2 passivation. An Au landing pad was deposited on the SiO_2 layer allowing for external probing and wire bonding. Finally, the crystal was cleaved along the m-plane of the substrate allowing for laser diodes with cavity length of approximately 1 mm.

I-V curves were recorded between the p- and n-contact (not shown). As expected a clear turn-on behavior around 4 V was recorded which is in agreement with the bandgap value. However, in addition to the main turn on, some minor leakage around 2 V was detected as well which is most likely related to leakage through pinholes in the SiO_2 layer. I-L spectra were recorded from the facet of the devices and are shown in Figure 3 for different injection current densities. The spectra recorded from the facet contain two main peaks: One peak at 345 nm related to the MQW and a secondary weaker peak at

550 nm (not shown in Figure 3). The latter is most likely due to reabsorption of the 345 nm light in the GaN substrate and re-emission via an impurity (carbon related impurity) (20). However, the emission of the MQW is much more efficient and intense compared to the yellow luminescence. Furthermore, by comparing emission collected from the surface to that from the edge we also find that there is some directional component to the MQW emission that reduces penetration of the light wave into the surrounding layers and confirms the benefit of the grown waveguide.

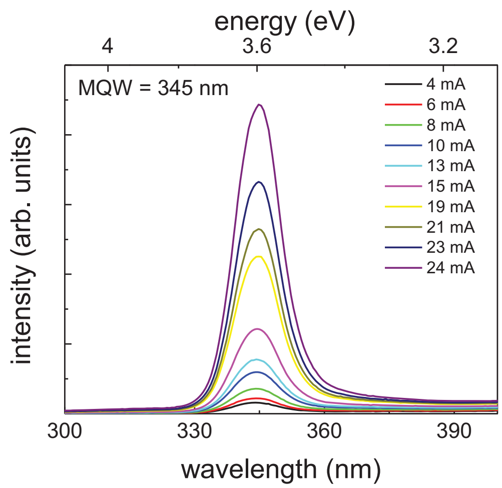

Figure 3: Evolution of the emission spectra of the UV laser diode with increasing current density.

The devices investigated for Figure 3 did not exhibit lasing even at applied current of as high as 200 mA. While a clear MQW related emission was observed at 345 nm at low currents, some red-shift was observed for increasing current densities indicating heating of the devices that reduces the internal quantum efficiency and potentially damages the lasers.

Possible limitations that hinder the achievement of lasing at this point are most likely related to the relatively low applied current density of < 5 kW/cm^2. Actively cooling the devices should allow for much higher current densities which will eventually result in electrically injected lasing.

IV. Conclusions

In summary, recent efforts to establish near UV laser diodes on single crystal substrates with lowest dislocations density are discussed. Optically pumped lasing has been demonstrated for a single quantum well devices emitting at 330 nm. Electrically injected devices were presented as well and light emission at 345 nm was observed. While lasing was not achieved a clear pathway towards electrically injected lasing is demonstrated.

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References

[1] Nakamura, S., T. Mukai, and M. Senoh, *Japanese Journal of Applied Physics*, **30,** L1998 (1991).

[2] Prentice, A., *Nutrition Reviews*, **66,** S153-S164 (2008).

[3] Kirste, R., N. Rohrbaugh, I. Bryan, Z. Zryan, R. Collazo, and A. Ivanisevic, *Annual Review of Analytical Chemistry*, **8,** (2015).

[4] Reddy, P., M.P. Hoffmann, F. Kaess, Z. Bryan, I. Bryan, M. Bobea, A. Klump, J. Tweedie, R. Kirste, S. Mita, M. Gerhold, R. Collazo, and Z. Sitar, *Journal of Applied Physics*, **120,** 185704 (2016).

[5] Ban, K., J.-i. Yamamoto, K. Takeda, K. Ide, M. Iwaya, T. Takeuchi, S. Kamiyama, I. Akasaki, and H. Amano, *Applied Physics Express*, **4,** 052101 (2011).

[6] Kirste, R., Q. Guo, J.H. Dycus, A. Franke, S. Mita, B. Sarkar, P. Reddy, J. LeBeau, M., R. Collazo, and Z. Sitar, *Applied Physics Express*, **11,** 082101 (2018).

[7] Bryan, I., Z. Bryan, S. Washiyama, P. Reddy, B. Gaddy, B. Sarkar, M.H. Breckenridge, Q. Guo, M. Bobea, J. Tweedie, S. Mita, D. Irving, R. Collazo, and Z. Sitar, *Applied Physics Letters*, **112,** 062102 (2018).

[8] Dycus, J.H., S. Washiyama, T.B. Eldred, Y. Guan, R. Kirste, S. Mita, Z. Sitar, R. Collazo, and J.M. LeBeau, *Applied Physics Letters*, **114,** 031602 (2019).

[9] Guo, W., Z. Bryan, J.Q. Xie, R. Kirste, S. Mita, I. Bryan, L. Hussey, M. Bobea, B. Haidet, M. Gerhold, R. Collazo, and Z. Sitar, *Journal of Applied Physics*, **115,** 103108 (2014).

[10] Xie, J., S. Mita, Z. Bryan, W. Guo, L. Hussey, B. Moody, R. Schlesser, R. Kirste, M. Gerhold, R. Collazo, and Z. Sitar, *Applied Physics Letters*, **102,** 171102-4 (2013).

[11] Martens, M., C. Kuhn, T. Simoneit, S. Hagedorn, A. Knauer, T. Wernicke, M. Weyers, and M. Kneissl, *Applied Physics Letters*, **110,** 081103 (2017).

[12] Deguchi, T., T. Azuhata, T. Sota, S. Chichibu, and S. Nakamura, *Materials Science and Engineering: B*, **50,** 251-255 (1997).

[13] Guo, Q., R. Kirste, P. Reddy, S. Mita, R. Collazo, and Z. Sitar. *Design Challenges for Mid-UV Laser Diodes*. in *2018 IEEE Research and Applications of Photonics In Defense Conference (RAPID)*. 2018.

[14] Yoshida, H., Y. Yamashita, M. Kuwabara, and H. Kan, *Applied Physics Letters*, **93,** 241106 (2008).

[15] Kneissl, M., *A Brief Review of III-Nitride UV Emitter Technologies and Their Applications*, in *III-Nitride Ultraviolet Emitters: Technology and Applications*, M. Kneissl and J. Rass, Editors. 2016, Springer International Publishing: Cham. p. 1-25.

[16] Hiramatsu, K., K. Nishiyama, M. Onishi, H. Mizutani, M. Narukawa, A. Motogaito, H. Miyake, Y. Iyechika, and T. Maeda, *Journal of Crystal Growth*, **221,** 316-326 (2000).

[17] Reddy, P., Q. Guo, J. Tweedie, S. Washiyama, F. Kaess, S. Mita, M.H. Breckenridge, R. Kirste, R. Collazo, A. Klump, B. Sarkar, and Z. Sitar. *Improving the Conductivity Limits in Si Doped Al Rich AlGaN*. in *2018 IEEE Research and Applications of Photonics In Defense Conference (RAPID)*. 2018.

[18] Sarkar, B., B.B. Haidet, P. Reddy, R. Kirste, R. Collazo, and Z. Sitar, *Applied Physics Express*, **10,** 071001 (2017).

[19] Sarkar, B., P. Reddy, A. Klump, F. Kaess, R. Rounds, R. Kirste, S. Mita, E. Kohn, R. Collazo, and Z. Sitar, *Journal of Electronic Materials*, **47,** 305-311 (2018).

[20] Kaess, F., S. Mita, J. Xie, P. Reddy, A. Klump, L.H. Hernandez-Balderrama, S. Washiyama, A. Franke, R. Kirste, A. Hoffmann, R. Collazo, and Z. Sitar, *Journal of Applied Physics*, **120,** 105701 (2016).