Fabrication of GaN-based micro-cavity light emitters

Yang Mei, Zhongming Zheng, Shuai Yang, Wei Ou, Hao Long, Leiying Ying, Baoping Zhang
Department of Microelectronics and Integrated Circuits
Xiamen University
Xiamen, China
bzhang@xmu.edu.cn

***Abstract*—GaN based microcavity light emitters are featured with small compact footprint, high quality (Q) factors, small mode volumes, and low power consumption. They are therefore attracting much attention in various fields, including photonics, visible light communications, quantum information, and cavity quantum electrodynamics (CQED). In this paper, we will introduce our recent progress in GaN-based micro-cavity light emitters including resonate cavity LEDs (RCLEDs) and vertical cavity surface emitting lasers (VCSELs).**

Keywords—GaN, micro-cavity, RCLEDs, VCSELs, exciton-polariton lasers

I. INTRODUCTION

Semiconductor based micro-cavities take the advantages of ultra-small compact footprint, high quality (Q) factors, small mode volumes, and low power consumption[1]. They have attracted great attention for decades because of the promising potential for both practical applications and fundamental research, such as novel ultralow threshold laser sources[2, 3], biomedical sensors[4], nonlinear optics, and strongly coupled cavity quantum electrodynamics[1]. To go towards the visible and ultraviolet spectral regions, GaN-based materials are ideal candidates for the micro-cavity light emitters because of their wide and tunable direct energy gaps and high emission efficiency. Benefiting from the large exciton binding energy, GaN-based micro-cavity is also very promising for the exciton-polariton lasers at room temperature, which can realize ultralow threshold and even threshold-less lasing[5, 6].

The two kinds of typical GaN-based micro-cavity light emitters for practical applications are RCLEDs and VCSELs, which are featured with a simple Fabry-Pérot (FP) cavity. After decades of research, GaN-based RCLEDs and VCSELs with different structures and emission wavelengths have been successfully fabricated, and device commercialization is not far off[7-10]. In this paper, we report our recent progress in GaN-based RCLEDs and VCSELs. For the RCLEDs, devices emitting in green and red spectral region with different cavity structure were fabricated. For the GaN-based VCSELs, we have demonstrated lasing action covering from UVC/UVA (optically pumped) to green spectral region (electrically pumped).

II. GAN BASED RCLEDS

A. *GaN-based green RCLED with Al bottom mirror and copper substrate*

The epi-wafer used to fabricate the green RCLED was grown on a c-plane patterned sapphire substrate (PSS). Figure 1 (a) shows the structure of the RCLED which has an Al bottom mirror (Cr/Al/Cr, 1/250/20 nm) and two pairs of TiO_2/SiO_2 top distributed Bragg reflector (DBR) to form the cavity. To fabricate the device, the PSS needs to be removed by using laser lift off (LLO) technique, and a copper plate was electroplated as the substrate to improve thermal dissipation. The detailed fabrication process can be found in our previous work[11]. The size of the device mesa is 500×500 μm^2. The reflectivity of the top dielectric DBR and bottom Al mirror exceed 65% and 80% in the 500 nm to ~700 nm wavelength region, respectively, as shown in Fig. 1(b).

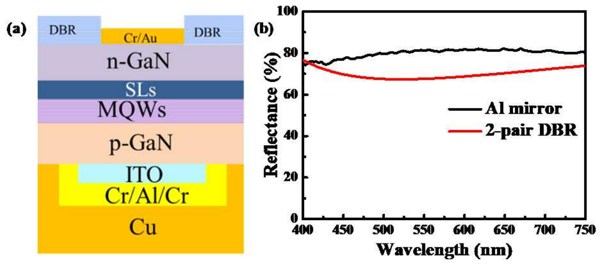

Fig. 1. (a) Schematic structure of the RCLED. (b) Reflectivity of the Al mirror and top DBR.

Figure 2 (a) shows the current-voltage (I-V) characteristics of the device. The reverse leakage current under bias voltage of -5V is relatively low, ~44.6 nA. Meanwhile, a very low turn-on voltage of 2.46 V at 20 mA was realized. The emission spectra of the device under currents from 0.1 mA to 5 mA are shown in Fig. 2 (b). Three peaks were clearly observed at 497 nm, 518 nm, and 545 nm, which are generated by the resonant-cavity effect of the FP cavity. The main peak at 518 nm has a linewidth of ~14 nm at 2 A/cm^2, much smaller than that of typical green LED without a cavity.

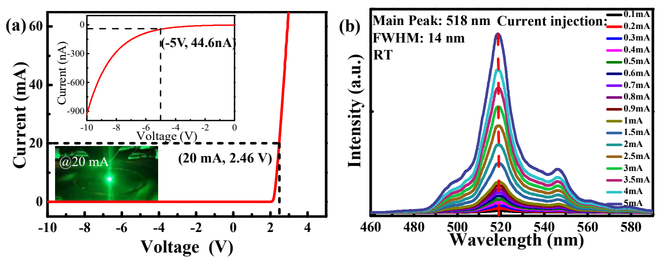

Fig. 2. (a) I-V characteristic of the RCLED, the inset shows the photo of an operating device. (b) EL spectra of the RCLED under different current.

The light output power (LOP) of the device was measured by an integrating sphere system, and is shown in Fig. 3. The LOP of the device was 11.1 mW at 50 A/cm^2, which is the highest LOP value for the GaN-based green RCLED with Al mirror[12, 13]. The higher LOP benefits

The National Key Research and Development Program of China (No.2017YFE0131500), the National Natural Science Foundation of China (Nos. 62234011, 62104204, 62174140 and U21A20493)

from the improved crystal quality of the active region owing to the PSS and superlattice insertion layers. In addition, the strain release caused by the LLO of PSS can also reduce the quantum confined Stark effect (QCSE) and improve the emission efficiency.

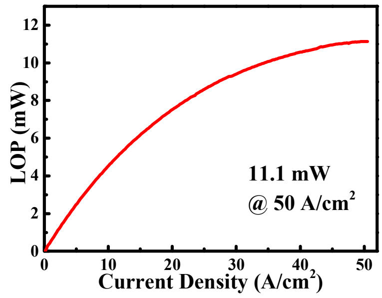

Fig. 3. Curve of the current density versus LOP of the RCLED.

B. GaN-based red RCLED with double dielectric DBRs

GaN-based RCLED emitting in red spectral range was also fabricated. The red RCLED has a copper substrate and a cavity with dual dielectric DBRs. The structure of the epi-wafer and the device are shown in Fig. 4. LLO of the sapphire substrate and thin film transfer are utilized in the device fabrication, and the detailed fabrication process can be found in our previous work[14].

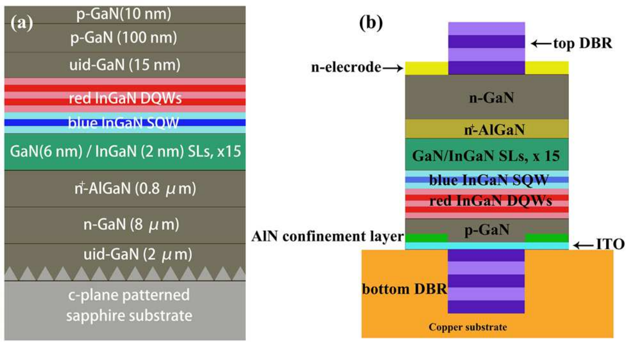

Fig. 4. (a) Structure of the epi-wafer. (b) Device structure of the RCLED with double dielectric DBRs.

We first measured the room-temperature (RT) photoluminescence (PL) spectra of the epitaxial wafer with varying excitation power, as shown in Fig. 5 (a). The spontaneous emission is centered at around 630 nm, and the slight blue shift with increasing excitation power was attributed to the screening of the QCSE. Figure 5 (b) shows the typical electroluminescence (EL) spectra of the red RCLED under 0.03 mA at RT. Resonant cavity effect led to four main longitudinal modes locating at 562, 581, 602, and 621 nm. Note that there are multi-peaks associated with each longitudinal mode, and this is attributed to the lateral confinement effect of the AlN confinement aperture. The fundamental mode exhibited the narrowest linewidth of 0.2 nm, and the highest Q factor was calculated by $\lambda/\Delta\lambda$ to be about 3010, which is a high value of the red RCLEDs. The inset is the photograph of a red RCLED in operation. A bright emission spot locates in the center of the aperture, indicating that the current and photons can be well confined in the AlN lateral confinement aperture.

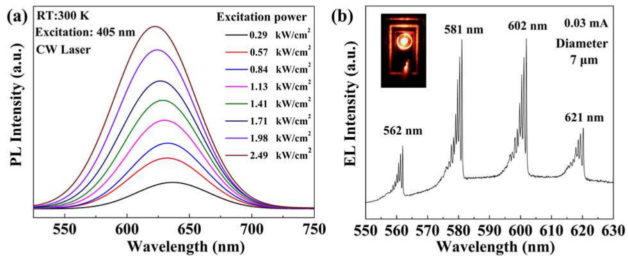

Fig. 5. (a) PL spectra of the epi-wafer. (b) EL spectrum and emission image of the red RCLED.

III. GaN-based VCSELs

GaN-based VCSELs are another typical kind of micro-cavity light emitters, and they offer several distinct advantages over conventional edge-emitting lasers, including lower threshold current, single longitudinal mode operation, high speed modulation, circular beam profiles, wafer-level testing, densely-packed two-dimensional arrays, etc. In this section, we will introduce our recent results on the optically pumped ultraviolet (UV) VCSELs and electrically injected green VCSELs.

A. Optically pumped UV VCSELs

Among various laser light realized by GaN-based materials, deep ultraviolet (DUV) laser has many potential applications, such as disinfection, medical treatment, biological sensing, lithography, and laser cutting[15]. However, it is very difficult to realize lasing in DUV region for GaN-based VCSELs. The specific challenges lie in the growth of AlGaN epilayer with high crystal quality and high Al composition, the strong optical absorption of material in DUV spectra region, and the difficulty of substrate removal and AlGaN thin film transfer. In view of the above difficulties, we developed the LLO technique for AlGaN layers with high Al mole fraction on sapphire substrate, and successfully grew AlGaN QW active region emitting in UVC band with high crystal quality. Based on these techniques, an optically pumped AlGaN-based VCSEL with double SiO_2/HfO_2 DBRs was fabricated, and lasing in UVC band was realized. The detailed fabrication process can be found in our previous work[16, 17]. The measured VCSEL lasing wavelength is 275.91 nm with a line width of 0.78 nm and a threshold power density of 1.21MW/cm^2, as shown in Fig. 6.

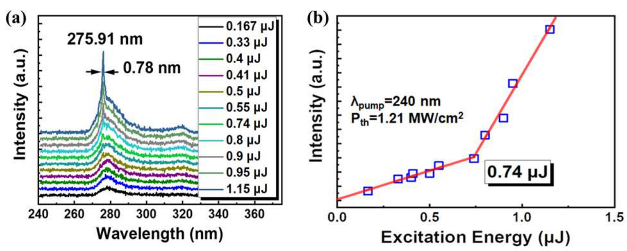

Fig. 6. (a) Emission spectra of the UVC VCSEL under different excitation power. (b) Emission intensity of the device as a function of excitation power.

GaN-based VCSELs lasing in UVA band was also fabricated by using double dielectric DBR structure and InGaN QW active region[18]. The active region has a resonate period gain (RPG) structure, that is, four $In_{0.1}Ga_{0.9}N$ (3nm)/GaN (5 nm) QWs were grown and divided into two groups separated by a 70-nm GaN spacing layer. The thickness of each layer was carefully designed to ensure that the two groups of QWs were located at two adjacent antinodes of the standing wave pattern inside the cavity. In addition, a wedge-shaped cavity was fabricated using the LLO and chemical mechanical polishing (CMP) technique, resulting in a graded cavity length in one device. The optical field inside the cavity can be modulated by the cavity length, so that tunable lasing at different wavelengths is realized at different points of a single VCSEL chip. The lasing wavelength extends from 376 to 409 nm, covering most of the UVA band below the band gap of GaN. The device structure and tunable lasing spectra are shown in Fig.7.

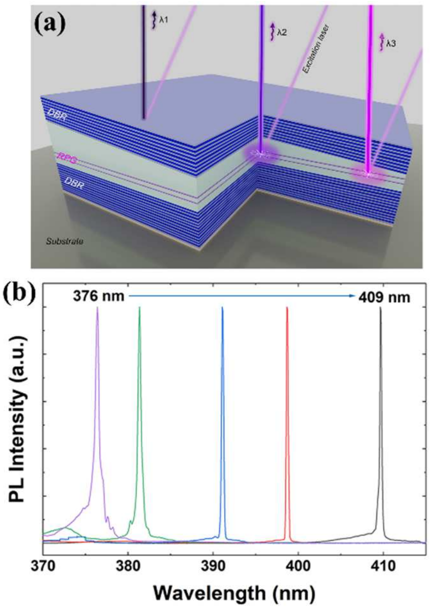

Fig. 7. (a) Structure of the UVA VCSEL with a wedge-shape cavity. (b) Tunable lasing spectra of the device from 376 to 409 nm.

B. *Electrically injected green VCSELs*

GaN-based VCSELs emitting in green are important light sources for the applications including micro-display, visible light communication, and bio-medical sensing. However, propelling GaN-based VCSELs from the blue to the green is not easy. In visible GaN-based VCSELs, two-dimensional InGaN QWs are commonly used as the active layers[8-10]. A higher indium content in the InGaN QW layer is necessary to extend the emission wavelength longer to green, however, causes more defects and a larger strain-induced built-in electric field. Defects are nonradiative recombination centers and built-in electric field causes QCSE which pulls apart electrons and holes to different sides of the QW, reducing their chances for radiative recombination[19]. These problems, however, can be well solved by using quantum dots (QDs) as active region. The GaN-based QDs are usually formed by the strain driven Stranski-Krastanov (S-K) growth mode. During the transition from 2 dimensional (2D) to 3D growth mode, the strain in the QDs is partly relaxed, leading to the reduction of the QCSE[20]. Apart from this, the carrier confinement of QDs can impede the carriers from being captured by defects. The small size of active region is also promising for low threshold lasing. Through this method, room temperature continuous wave operation of green-emitting GaN-based VCSELs with double dielectric DBR structure was realized. Figure 8 shows the device structure and the images of a single VCSEL and device array, detailed device fabrication process can be found in our previous works[2, 21]. Figure 9 show the lasing spectrum and output power as a function of injected current. Single mode lasing at 560.4 nm was realized and the threshold current is as low as 0.61 mA.

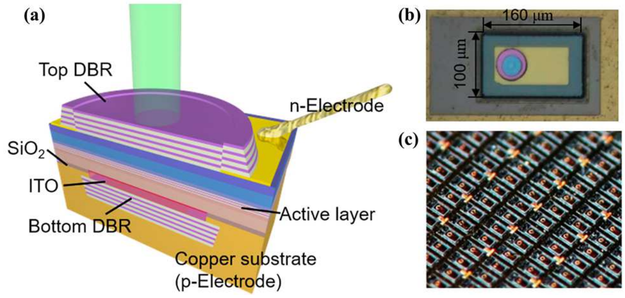

Fig. 8. (a) Device structure of the green VCSEL with double dielectric DBRs. (b) A photon of a single VCSEL. (c) A photo of the device array.

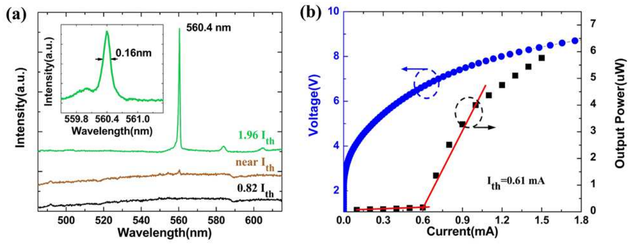

Fig. 9. (a) Emission spectra of the UVC VCSEL under different excitation power. (b) Emission intensity of the device as a function of excitation power.

IV. CONCLUSIONS

In summary, we have fabricated GaN-based micro cavity light emitters including RCLEDs emitting in green and red, optically pumped UVC and UVA VCSELs, and electrically injected green QD VCSELs. These results open up opportunities to design and fabricate GaN-based micro cavity light emitters for various practical applications.

REFERENCES

[1] K. J. Vahala, "Optical microcavities," *Nature,* vol. 424, no. 6950, pp. 839-846, 2003.
[2] Y. Mei, G.-E. Weng, B.-P. Zhang, J.-P. Liu, W. Hofmann, L.-Y. Ying *et al.*, "Quantum dot vertical-cavity surface-emitting lasers covering the 'green gap'," *Light: Science & Applications,* vol. 6, no. 1, pp. e16199-e16199, 2017.
[3] D. Wang, T. Zhu, R. A. Oliver, and E. L. Hu, "Ultra-low-threshold InGaN/GaN quantum dot micro-ring lasers," *Optics letters,* vol. 43, no. 4, pp. 799-802, 2018.
[4] E. Gil-Santos, C. Baker, D. Nguyen, W. Hease, C. Gomez, A. Lemaître *et al.*, "High-frequency nano-optomechanical disk resonators in liquids," *Nature nanotechnology,* vol. 10, no. 9, pp. 810-816, 2015.
[5] J. Wu, H. Long, X. Shi, S. Luo, Z. Chen, Z. Feng *et al.*, "Polariton lasing in InGaN quantum wells at room temperature," *Opto-Electronic Advances,* vol. 2, no. 12, pp. 190014-1-190014-5, 2019.
[6] J. Wu, X. Shi, H. Long, L. Chen, L. Ying, Z. Zheng *et al.*, "Large Rabi splitting in InGaN quantum wells microcavity at room temperature," *Materials Research Express,* vol. 6, no. 7, p. 076204, 2019.
[7] M. Ito, T. Hamaguchi, T. Makino, K. Hayashi, J. A. Kearns, M. Ohara *et al.*, "Highly efficient operation and uniform characteristics of curved mirror vertical-cavity surface-emitting lasers," *Applied Physics Express,* vol. 16, no. 1, p. 012006, 2023.

[8] M. Kuramoto, S. Kobayashi, T. Akagi, K. Tazawa, K. Tanaka, T. Saito *et al.*, "High-power GaN-based vertical-cavity surface-emitting lasers with AlInN/GaN distributed Bragg reflectors," *Applied Sciences,* vol. 9, no. 3, p. 416, 2019.
[9] K. Terao, H. Nagai, D. Morita, S. Masui, T. Yanamoto, and S.-i. Nagahama, "Blue and green GaN-based vertical-cavity surface-emitting lasers with AlInN/GaN DBR," in *Gallium Nitride Materials and Devices XVI*, 2021, vol. 11686: SPIE, p. 116860E.
[10] H. Wu, H. Li, S.-Y. Kuo, B.-Y. Chen, T.-C. Lu, and H. Huang, "High output power GaN-based green resonant-cavity light-emitting diodes with trapezoidal quantum wells," *IEEE Transactions on Electron Devices,* vol. 67, no. 9, pp. 3650-3654, 2020.
[11] S. Yang, H. Xu, H. Long, L. Ying, R. Luo, M. Zhong *et al.*, "GaN-based green resonant-cavity light-emitting diodes with Al mirror and copper plate," *Optics Letters,* vol. 47, no. 11, pp. 2858-2861, 2022.
[12] F. B. Naranjo, S. Fernández, F. Calle, M. A. Sánchez-García, and E. Calleja, "From Ultraviolet to Green InGaN-Based Conventional and Resonant-Cavity Light-Emitting Diodes Grown by Molecular Beam Epitaxy," *physica status solidi (a),* vol. 192, no. 2, pp. 341-347, 2002.
[13] S. Y. Huang, R. H. Horng, P. L. Liu, J. Y. Wu, H. W. Wu, and D. S. Wuu, "Thermal Stability Improvement of Vertical Conducting Green Resonant-Cavity Light-Emitting Diodes on Copper Substrates," *IEEE Photonics Technology Letters,* vol. 20, no. 10, pp. 797-799, 2008, doi: 10.1109/LPT.2008.921120.
[14] W. Ou, Y. Mei, D. Iida, H. Xu, M. Xie, Y. Wang *et al.*, "InGaN-Based Orange-Red Resonant Cavity Light-Emitting Diodes," *Journal of Lightwave Technology,* vol. 40, no. 13, pp. 4337-4343, 2022.
[15] Z. Zhang, M. Kushimoto, T. Sakai, N. Sugiyama, L. J. Schowalter, C. Sasaoka *et al.*, "A 271.8 nm deep-ultraviolet laser diode for room temperature operation," *Applied Physics Express,* vol. 12, no. 12, p. 124003, 2019.
[16] Z. Zheng, Y. Wang, J. Hoo, S. Guo, Y. Mei, H. Long *et al.*, "High-quality AlGaN epitaxial structures and realization of UVC vertical-cavity surface-emitting lasers," *Science China Materials,* 2023/01/17 2023.
[17] Z. Zheng, Y. Mei, H. Long, J. Hoo, S. Guo, Q. Li *et al.*, "AlGaN-based deep ultraviolet vertical-cavity surface-emitting laser," *IEEE Electron Device Letters,* vol. 42, no. 3, pp. 375-378, 2021.
[18] Y. Mei, T.-R. Yang, W. Ou, Z.-M. Zheng, H. Long, L.-Y. Ying *et al.*, "Low-threshold wavelength-tunable ultraviolet vertical-cavity surface-emitting lasers from 376 to 409 nm," *Fundamental Research,* vol. 1, no. 6, pp. 684-690, 2021.
[19] J.-H. Ryou, P. D. Yoder, J. Liu, Z. Lochner, H. Kim, S. Choi *et al.*, "Control of quantum-confined stark effect in InGaN-based quantum wells," *IEEE Journal of Selected Topics in Quantum Electronics,* vol. 15, no. 4, pp. 1080-1091, 2009.
[20] L. Wang, L. Wang, C. J. Chen, K. C. Chen, Z. Hao, Y. Luo *et al.*, "Green InGaN quantum dots breaking through efficiency and bandwidth bottlenecks of micro‐LEDs," *Laser & Photonics Reviews,* vol. 15, no. 5, p. 2000406, 2021.
[21] G. Weng, Y. Mei, J. Liu, W. Hofmann, L. Ying, J. Zhang *et al.*, "Low threshold continuous-wave lasing of yellow-green InGaN-QD vertical-cavity surface-emitting lasers," *Optics Express,* vol. 24, no. 14, pp. 15546-15553, 2016.