Full-Color MicroLEDs for Display Technologies

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Abstract: The red, green, blue micro light-emitting diodes (µLEDs) using InGaN/AlGaN core-shell nanowire heterostructures, grown on a silicon substrate by molecular beam epitaxy are demonstrated. These µLEDs are promising for microLED display technologies.

1. Introduction

InGaN nanowire µLEDs are an excellent potential candidate for developing novel micro-LED displays [1] since the energy bandgap of InGaN compounds can be varied from 3.4 eV (GaN) to 0.65 eV (InN) [2], covering the entire visible spectrum for display applications. Inorganic micro light-emitting diodes (µLEDs) have been receiving an intensive attention for microLED displays, applicable for smartwatch, smartphone, television, billboards, and augmented reality and virtual reality devices. Significant efforts have demonstrated microLED displays and bring them to the market [1, 3, 4]. To demonstrate a µLEDs display, there are several essential stages [5], consisting of making µLEDs, transferring them to a backplane, and precisely controlling each individual LED with transistors [6, 7]. Herein, we present the right type of red, green, and blue (RGB) µLEDs satisfactory for the displays. The µLEDs have a high brightness, high efficiency, and durability, excellent fit to microLED displays. Besides, different approaches for making RGB µLEDs for microLED displays [8, 9], the GaN-on-silicon monolithic microLED display technology is an excellent promising candidate since it allows the direct integration of µLEDs and driving transistors on a single silicon wafer, addressing a main hurdle of transferring of millions of µLEDs onto a backplane. The RGB colors of µLEDs are engineered by changing the composition of indium in the InGaN active region of a nanowire µLED. This can be done by adjusting the growth temperature and/or In/Ga flux ratios in the MBE growth conditions [10, 11].

2. Experiment

Vertical InGaN/AlGaN core-shell nanowires of µLEDs were grown by a plasma-assisted Veeco Gen II MBE (PAMBE) system. The growth conditions are detailed in our recent publication [12]. The schematic structure of the single InGaN/AlGaN nanowire LED on a Si substrate is presented in Figure 1(a). The active region of an LED nanowire structure has ten quantum wells. Each quantum well includes a 3nm InGaN and 3nm AlGaN barrier. During the growth of AlGaN barriers, an AlGaN shell spontaneously forms, enabling a unique InGaN/AlGaN core-shell structure. The SEM image of grown nanowires and the optical microscope image of a µLED device are shown in Figure 1(b) and (c), respectively. The InGaN nanowires are relatively identical and their length, controlled by the growth duration, is approximately 580 nm. After the conventional fabrication process, a completed µLED device has the circle lighting window of 50 µm in diameter that is connected to a square electrode pad.

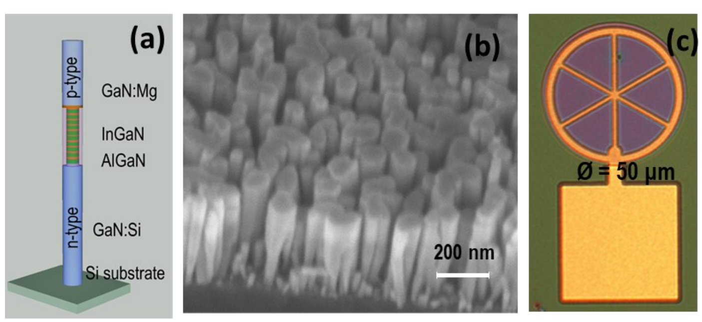

Figure 1. Schematic structure of a nanowire µLED with ten InGaN/AlGaN quantum well heterostructures (a); a 45-degree tilted SEM image of InGaN/AlGaN nanowires on the Si substrate (b); and an optical image of the µLED with its electrode pad (c).

3. Results

The *I-V* curves of the µLEDs in Figure 2(a) clearly show the turn-on voltages of the red, green, and blue µLEDs approximately at 1.6 V, 3.5 V, and 4.6 V. The lower indium of the composition has a higher energy bandgap, and results in a higher turn-on voltage of the devices [13]. The *I-V* characteristics also indicate the µLED devices with a low resistance and good fabrication processes have been achieved.

The normalized electroluminescence (EL) spectra of the nanowire RGB µLEDs were investigated at 200 mA current and under the pulse biasing condition to avoid the heating effect. The 645 nm red, 550 nm green, and 475 nm blue emissions result from the composition of $In_{0.43}Ga_{0.57}N$, $In_{0.32}Ga_{0.68}N$, and $In_{0.21}Ga_{0.79}N$, respectively. The less indium composition, the higher energy bandgap, makes the light emissions shift toward the blue region. The emission color of the µLEDs can be controlled by adjusting the ratio of Ga/In flux and the substrate temperature during the MBE growth. For instance, the peak emission wavelength can be shifted from red to blue by gradually increasing the growth temperature of InGaN in the active region from 580 °C to 650 °C with the ramping rate of 10 °C/min.

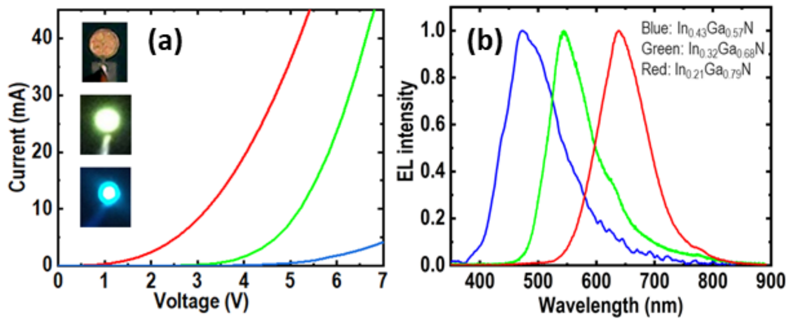

Figure 2. *I-V* characteristics of RGB LEDs and their optical corresponding microscopy images (a), and electroluminescence characteristics of 475 nm blue, 550 nm green, 645 nm red µLEDs measured (b).

4. Conclusions

We have successfully demonstrated µLEDs using InGaN/AlGaN core-shell nanowire heterostructures MBE grown on silicon substrates. The strong and stable emissions of RGB µLEDs by indium composition engineering show promise in monolithic microLED display applications. Provided progressive demands for electronic devices, opportunities for high efficiency, high color rendering properties, and low power consumption µLEDs used as subpixels in microLED displays are huge.

5. References

[1] X. Zhang *et al.*, "Active Matrix Monolithic LED Micro-Display Using GaN-on-Si Epilayers," *IEEE Photonics Technology Letters,* vol. 31, no. 11, pp. 865-868, 2019.

[2] B. Arnaudov *et al.*, "Energy position of near-band-edge emission spectra of InN epitaxial layers with different doping levels," *Physical Review B,* vol. 69, no. 11, 2004.

[3] E. Virey, "Are microLEDs really the next display revolution?," *Information Display,* vol. 3, no. 18, p. 28, 2018.

[4] L. Zhao Jun, C. Wing Cheung, W. Ka Ming, and L. Kei May, "360 PPI Flip-Chip Mounted Active Matrix Addressable Light Emitting Diode on Silicon (LEDoS) Micro-Displays," *Journal of Display Technology,* vol. 9, no. 8, pp. 678-682, 2013.

[5] K. Ding, V. Avrutin, N. Izyumskaya, Ü. Özgür, and H. Morkoç, "Micro-LEDs, a Manufacturability Perspective," *Applied Sciences,* vol. 9, no. 6, 2019.

[6] L. Zhang, F. Ou, W. C. Chong, Y. Chen, and Q. Li, "Wafer-scale monolithic hybrid integration of Si-based IC and III-V epi-layers-A mass manufacturable approach for active matrix micro-LED micro-displays," *Journal of the Society for Information Display,* vol. 26, no. 3, pp. 137-145, 2018.

[7] R. S. Cok *et al.*, "Inorganic light-emitting diode displays using micro-transfer printing," *Journal of the Society for Information Display,* vol. 25, no. 10, pp. 589-609, 2017.

[8] K.-J. Chen *et al.*, "Resonant-Enhanced Full-Color Emission of Quantum-Dot-Based Display Technology Using a Pulsed Spray Method," *Advanced Functional Materials,* vol. 22, no. 24, pp. 5138-5143, 2012.

[9] C.-H. Teng, L. Zhang, H. Deng, and P.-C. Ku, "Strain-induced red-green-blue wavelength tuning in InGaN quantum wells," *Applied Physics Letters,* vol. 108, no. 7, 2016.

[10] R. Wang, H. P. Nguyen, A. T. Connie, J. Lee, I. Shih, and Z. Mi, "Color-tunable, phosphor-free InGaN nanowire light-emitting diode arrays monolithically integrated on silicon," *Opt Express,* vol. 22 Suppl 7, pp. A1768-75, Dec 15 2014.

[11] M. R. Philip *et al.*, "Controlling color emission of InGaN/AlGaN nanowire light-emitting diodes grown by molecular beam epitaxy," *Journal of Vacuum Science & Technology B, Nanotechnology and Microelectronics: Materials, Processing, Measurement, and Phenomena,* vol. 35, no. 2, 2017.

[12] H. Q. T. Bui *et al.*, "Full-color InGaN/AlGaN nanowire micro light-emitting diodes grown by molecular beam epitaxy: A promising candidate for next generation micro displays," *Micromachines,* vol. 10, no. 8, p. 492, 2019.

[13] E. F. Schubert, *Light-Emitting Diodes*. Cambrigde university press, 2006.