Received 14 July 2019; revised 12 November 2019; accepted 9 January 2020. Date of publication 17 January 2020; date of current version 5 March 2020.
The review of this paper was arranged by Editor A. Nathan.

*Digital Object Identifier 10.1109/JEDS.2020.2967476*

# Process Integration and Interconnection Design of Passive-Matrix LED Micro-Displays With 256 Pixel-Per-Inch Resolution

SHUO-HUANG YUAN [1], SHIH-SIANG YAN [2], YU-SHIUAN YAO [1], CHUNG-CHENG WU [1], RAY-HUA HORNG [3] (Fellow, IEEE), AND DONG-SING WUU [1,4,5] (Senior Member, IEEE)

1 Department of Materials Science and Engineering, National Chung Hsing University, Taichung 40227, Taiwan
2 Graduate Institute of Precision Engineering, National Chung Hsing University, Taichung 40227, Taiwan
3 Institute of Electronics, National Chiao Tung University, Hsinchu 30010, Taiwan
4 Innovation and Development Center of Sustainable Agriculture, National Chung Hsing University, Taichung 40227, Taiwan
5 Research Center for Sustainable Energy and Nanotechnology, National Chung Hsing University, Taichung 40227, Taiwan

CORRESPONDING AUTHOR: D.-S. WUU (e-mail: dsw@nchu.edu.tw)

This work was supported in part by the Ministry of Science and Technology of Taiwan under Grant 107-2221-E-005-058-MY3 and Grant 108-2221-E-005-072-MY3, and in part by the "Innovation and Development Center of Sustainable Agriculture" From the Featured Areas Research Center Program within the Framework of the Higher Education Sprout Project by the Ministry of Education of Taiwan.

**ABSTRACT** A 0.28-inch InGaN-based blue micro-LED display with 256 pixel-per-inch resolution and a pitch of 100 $\mu$m was successfully fabricated in this study. A thick Ti/Al/Ti/Au interconnection metal was deposited on the n-type gallium nitride (n-GaN) region to reduce the interconnection resistance. The micro-LED array with interconnection metal exhibits better electrical property consistency as compared with that of the traditional one. The output power, forward voltage, and external quantum efficiency of micro-LED, which measured under 1-mA current injection with the full lighting mode, are 0.8 mW, 3.0 V, and 10%, respectively. This technique has the potential to integrate InGaN-based LEDs with quantum dots for full-color applications.

**INDEX TERMS** Micro-LED, InGaN, display, interconnection, external quantum efficiency.

## I. INTRODUCTION

The light-emitting diodes (LEDs) belonging to solid-state self-emissive devices are popular in the industry applications because they own many merits such as less energy consumption, long-term stability, high brightness, shorter response time and extremely environment operation [1]–[4]. Recently, the industries are seeking higher resolution LED displays with the pixel size smaller than 100 $\mu$m. These devices have the most advanced technologies with low-power optoelectronics capability on the market currently. Displays made of micro-LED arrays have high potential for applications such as automotive, self-emissive displays, military applications, wearable devices, biologic transducers, and medical treatments [5]–[7].

Today, the high-resolution full-color display with smaller pixel size is of the currently developing tendency to integrate red, green, and blue three different color micro-LEDs in one single display. Those displays belong to the active-matrix display where each pixel can be controlled by a thin-film transistor (TFT) [8], [9]. For active-matrix displays, the micro-LED and TFT are needed to make alignment precisely. This bonding technology in actual emissive displays fabrication still has several tough challenges. One of the main challenges in the pixel control is that the control circuit has to use the current-driving mode to control each pixel in the display instead of using the voltage-controlled mode. The passive-matrix micro-LED display is another option which has advantages such as cost reduction, easy fabrication, and suitable mass production. Nevertheless, most of the investigations focused on blue micro-LEDs due to the insulating sapphire substrate and transparent epitaxial substrate [10].

The contact resistance lowering between electrode and semiconductor had been reported [11]–[14]. However, those investigations focused on a single chip instead of an LED array. For display, the interconnection will be one of the most important issues that will influence the array performance in

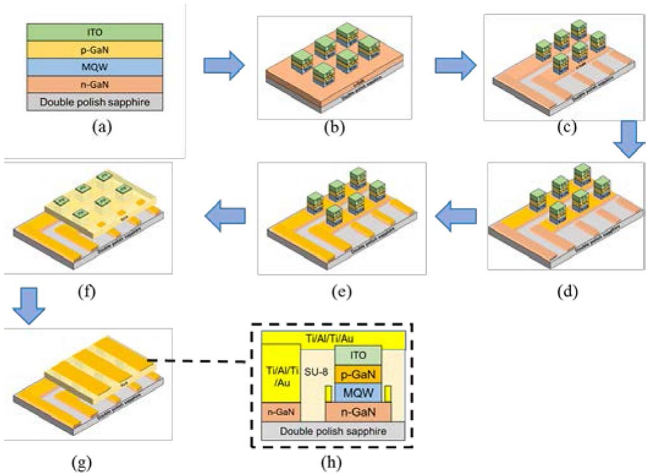


**FIGURE 1.** **Process flow of 64 × 32 pixels blue micro-LED display chip: (a) ITO deposition, (b) epi-layer structure etching to n-GaN, (c) n-GaN isolation, (d) thin n-interconnect metal deposition, (e) thick metal deposition, (f) planarization by SU-8, (g) column metal line deposition, (h) cross-section diagram of the blue micro-LED display array.**

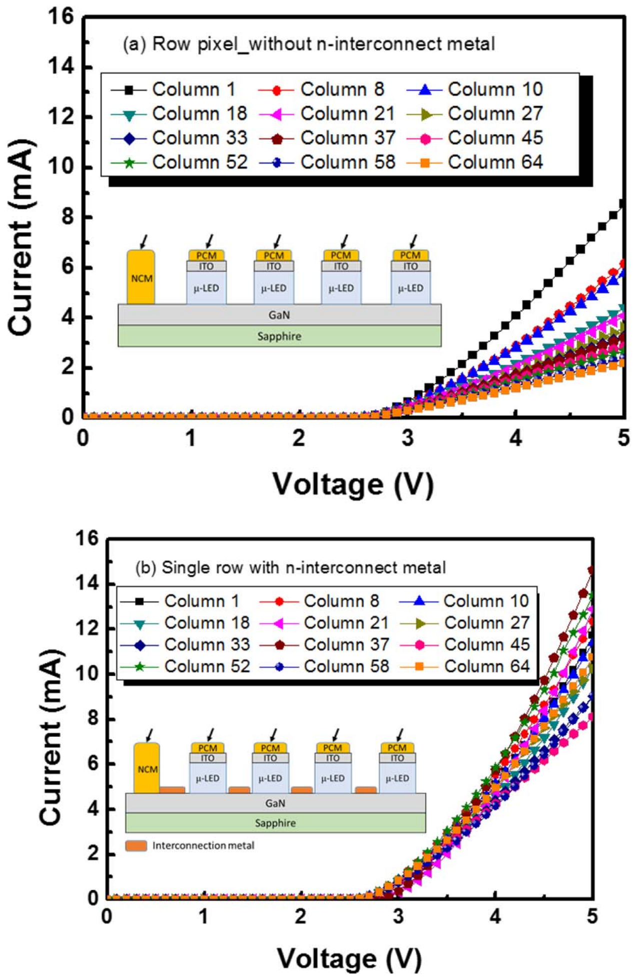


**FIGURE 2.** **I-V curves of pixels (a) without and (b) with n-interconnect metal in a single row.**

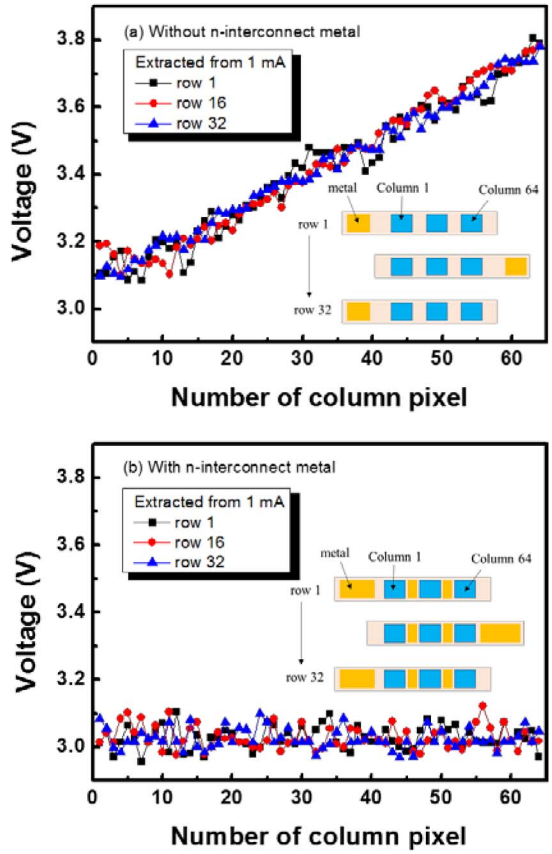


**FIGURE 3.** **$V_f$ variations of column pixels in three individual rows (a) without and (b) with n-interconnect metal. Inset figures are the schematic diagram of measurement.**

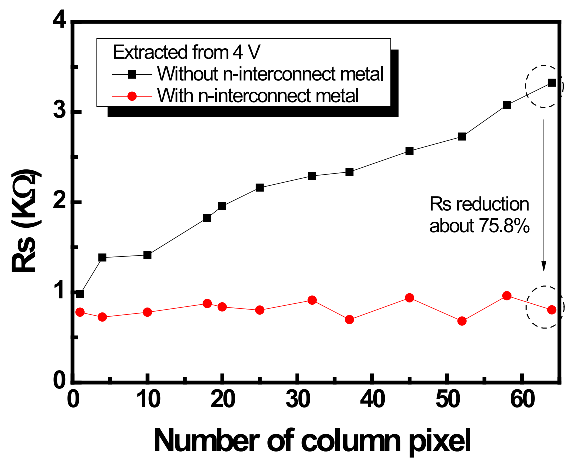


**FIGURE 4.** **Series resistance of the column pixels in a single row.**

micro-LEDs. However, the interconnection influence on the performance of micro-LEDs in the array is rarely reported. Our previous work had been successfully demonstrated the characteristics and fabrication process of the red-light micro-LED display [15], [16]. However, the fabrication process of blue-light micro-LED is different from that of the red-light micro-LED because of the epi-structure. Moreover, the previous red-light micro-LED report was lack of metallic interconnection. Accordingly, in this study, we investigate the micro-LED panel with Ti/Al/Ti/Au interconnection metal.

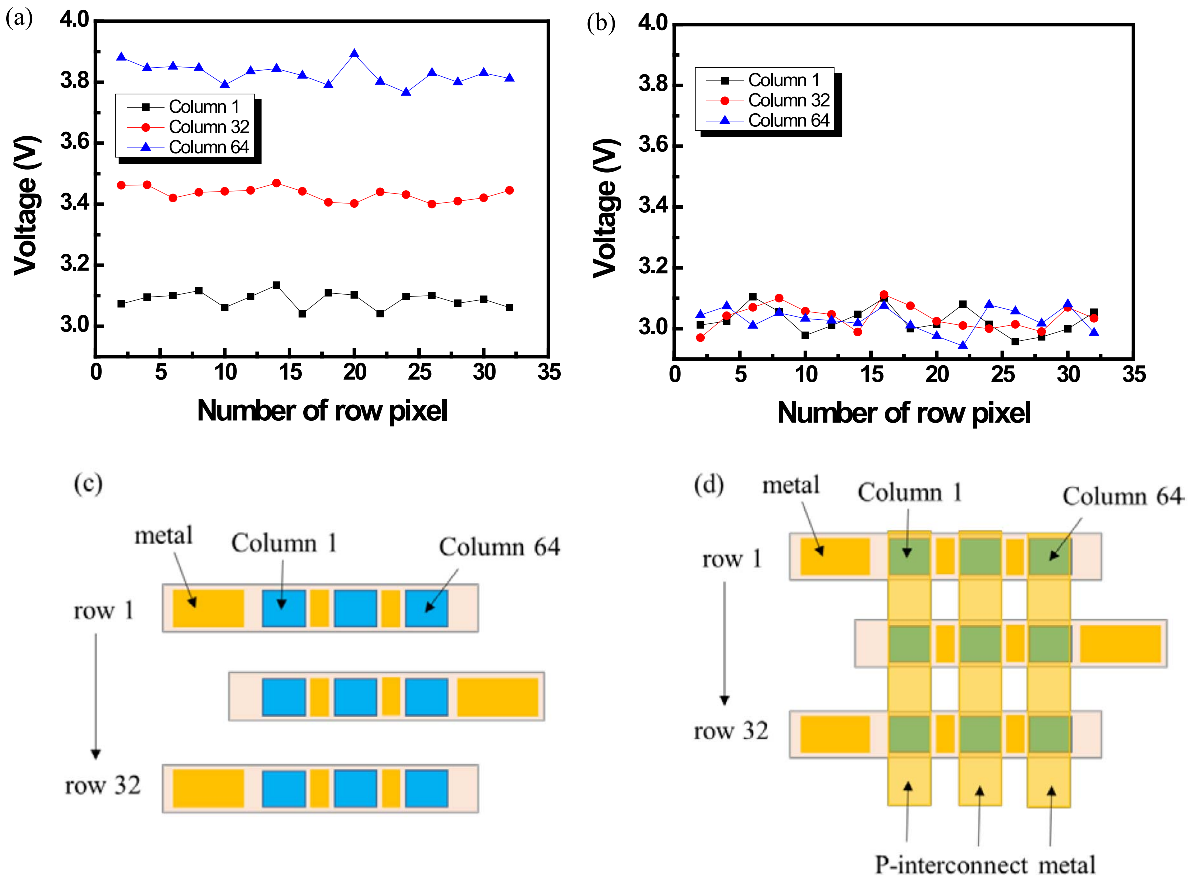


**FIGURE 5.** $V_f$ **variations of row pixels (a) without and (b) with p-interconnect metal in three individual columns (extracted from 1 mA). The schematic diagrams of measurement (c) without and (d) with p-interconnect metal.**

The ohmic contact of Ti/Al/Ti/Au to n-GaN has a lower contact resistance than other bi-layer and tri-layer metals. The fabrication processing and the micro-LED array performance will be discussed in detail.

## II. EXPERIMENTAL

There are several process steps for the micro-LED display fabrication. First, the blue LED epilayers were grown on sapphire substrates by metalorganic chemical vapor deposition. The epi-structure consisted of an undoped GaN buffer, n-type GaN current spreading layer, InGaN and GaN stacked multiple quantum wells and p-type GaN electron blocking layer. Secondly, an electron-beam-evaporated ITO layer was deposited on the p-type GaN layer for current spreading. An additional thermal anneal treatment was performed in order to reduce the contact resistance (ohmic contact) between the ITO and p-GaN. Thirdly, the mesa region was defined by dry etching using an inductively coupled plasma etcher. Afterward, the thin n-interconnect metal and thick Ti/Al/Ti/Au were deposited on the surface of the exposed n-GaN layer surface. Fourthly, a thick SU-8 passivation layer was deposited by spin coating which also had a planarization function to decrease the gap between the n- and p-electrodes. A total thickness of approximately 3.6 μm p-electrode consisted of Ti/Al/Ti/Au with a thickness of 30 nm/3.5 μm/40 nm/60 nm was deposited using an electron-beam evaporator. The micro-LED (pixel size of 50*50 $\mu m^2$) display with 64 × 32 pixels was achieved, where details of the process flow is shown in Fig. 1.

## III. RESULT AND DISCUSSION

The current-voltage (I-V) characteristics of the micro-LEDs in a single row are shown in Fig. 2. The pixels with increase of the distance between the pixel and n-electrode under voltage of 5V exhibit current reduction in these two devices. It was found that the thin n-interconnection metal had a function of improving the LED electrical performance. The forward voltage ($V_f$) variation, which extracted from row 1, 16, and 32, is used to apprehend the electrical performance of the array. Notice that those pixels p-electrodes ITO are isolated.

Fig. 3 shows the $V_f$ measurement results for each pixel from three rows (1, 16 and 32) in a micro-LED array. Under an injection current of 1 mA, the pixel $V_f$ value of the micro-LED array without n-interconnection metal gradually increased from 3.1 V for pixel 1 to 3.7 V for pixel 64 [Fig. 3(a)], whereas it becomes stable for that of with the n-interconnection metal [in Fig. 3(b)]. The $V_f$

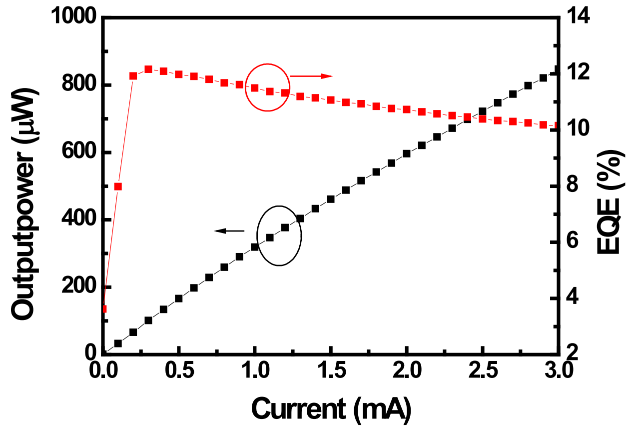


**FIGURE 6.** Light Output power and EQE of micro LED display as a function of the driving current.

variation increases when the driving current is higher than 5 mA (Fig. 2(b)), which can be attributed to the nonuniformity of the injection current distribution [17]. The variation in $V_f$ data shows the same trend as those pixels located in various row lines. The smaller variation in pixel $V_f$ data can be attributed to the improvement of series resistance.

Fig. 4 shows the series resistance (Rs) of the column pixels in a single row. The column pixels without n-interconnect metal exhibited series resistance values increasing from 0.9 kΩ for pixel 1 to 3.3 kΩ for pixel 64. The dramatic increase in the Rs can be attributed to the current flowing through the high-resistivity n-GaN layer. A metallic interconnection line with a low resistivity can solve this issue. For the device with n-interconnect metal, the Rs variation showed less dependence on the column position. Furthermore, the Rs showed dramatically decrease by about 75.5% in magnitude for the pixel of column 64. The result confirmed that the driving current flows through the pixel via the metallic interconnection line instead of the n-GaN epilayer.

Fig. 5 shows the $V_f$ variation of the micro-LEDs in an array with thick p-interconnect metal and the schematic diagrams of measurement. All of the $V_f$ of pixels are extracted from the injection current of 1 mA. The $V_f$ of the column pixels without p-interconnection exhibits large variation. This phenomenon is attributed to the high resistivity which results from the pixels with increasing the distance between the contact metal pads and pixel. However, the $V_f$ keeps unchanged when the thick p-interconnect metal has deposited on the top of the pixels. This result evidences that the p-interconnect metal can lower the resistivity between the pixels.

Fig. 6 shows the optical output power and external quantum efficiency (EQE) as a function of the injection current ranging from 0 to 3 mA. It was found that an output power of 101 μW and a maximum EQE of 12.1% were achieved in the LED sample under an injecting current of 0.3 mA. When the injection current increased to 3 mA, the EQE of the LED decreased to 10.1%. The efficiency droop phenomenon could be attributed to the high local carrier concentration in the LED which enhanced the Auger recombination [17]. However, the output power significantly increases to 847 μW. The functional demonstration and thermal analysis images of the micro-LED display are shown in Fig. 7. The display shows an excellent thermal distribution and the temperature deviation of only 0.2°C. After 30 min operation, the temperature of the micro-LED display only increases about 3°C with a temperature deviation of 0.17°C.

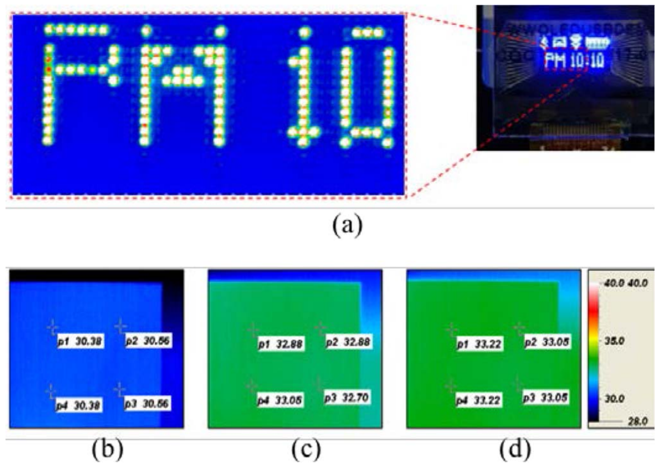


**FIGURE 7.** (a) Function demonstration of the blue micro-led display with infrared thermographer (left figure). Thermal analysis image of the micro-led display after operates (b) 1, (c) 10, and (d) 30 min.

## IV. CONCLUSION

We have demonstrated the blue micro-LED display with a resolution of 256 pixel-per-inch (64 × 32 pixels), a pixel size of 50 μm, and the panel size of 0.25 $cm^2$. The metallic interconnection will influence the display opto-electrical performance. The electrical performance of the LEDs with the thin Ti/Al/Ti/Au n-interconnection metal in a single row was increased from 37.3% for pixel 1 to 391.5% for pixel 64 as analysis of the I-V characteristics. Besides of the injection current improvement, we found that it can stabilize the $V_f$ of the pixels. The major reason was that the series resistance had been modification via n-interconnection metal. The maximum EQE and optical output power of the LED can achieve to 101 μW and 12.1%. This blue micro-LED display shows excellent thermal distribution. After operation 30 min, the temperature only increases about 3°C with a deviation of 0.17°C. The results suggested that the blue micro-LED display presented in this research has high potential to replace the passive organic light-emitting display in the current medium-small sized panel market.

## REFERENCES

[1] G. Chen *et al.*, "Performance of high-power III-Nitride light emitting diodes," *Phys. Status Solidi A*, vol. 205, no. 5, pp. 1086–1092, 2008.
[2] J. Day, J. Li, D. Y. C. Lie, C. Bradford, J. Y. Lin, and H. X. Jiang, "III-Nitride full-scale high-resolution microdisplays," *Appl. Phys. Lett.*, vol. 99, no. 3, Art. no. 031116, 2011.
[3] T. Wu *et al.*, "Mini-LED and micro-LED: Promising candidates for the next generation display technology," *Appl. Sci.*, vol. 8, no. 9, Art. no. 1557, 2018.

[4] S. Pimputkar, J. S. Speck, S. P. DenBaars, and S. Nakamura, "Prospects for LED lighting," *Nat. Photon.*, vol. 3, pp. 180–182, Apr. 2009.
[5] J. Herrnsdorf *et al.*, "Active-matrix GaN micro light-emitting diode display with unprecedented brightness," *IEEE Trans. Electron Devices*, vol. 62, no. 6, pp. 1918–1925, Jun. 2015.
[6] S. Me *et al.*, "High-bandwidth white-light system combining a micro-LED with Perovskite quantum dots for visible light communication," *ACS Appl. Mater. Interfaces*, vol. 10, no. 6, pp. 5641–5648, 2018.
[7] P. Tian *et al.*, "Fabrication, characterization and applications of flexible vertical InGaN micro-light emitting diode arrays," *Opt. Exp.*, vol. 24, no. 1, pp. 699–707, 2016.
[8] W.-S. Shin *et al.*, "A driving method of pixel circuit using a-IGZO TFT for suppression of threshold voltage shift in AMLED displays," *IEEE Electron Device Lett.* vol. 38, no. 6, pp. 760–762, Jun. 2017.
[9] J. G. Um *et al.*, "Active-matrix GaN $\mu$-LED display using oxide thin-film transistor backplane and flip chip LED bonding," *Adv. Electron. Mater*. vol. 5, no. 3, Art. no. 1800617, Mar. 2019.
[10] J. Herrnsdorf *et al.*, "Active-matrix GaN micro light-emitting diode display with unprecedented brightness," *IEEE Trans. Electron Devices*, vol. 62, no. 6, pp. 1918–1925, Jun. 2015.
[11] N. Nagata, T. Senga, M. Iwaya, T. Takeuchi, S. Kamiyama, and I. Akasaki, "Reduction of contact resistance in V-based electrode for high AlN molar fraction n-type AlGaN by using thin $SiN_x$ intermediate layer," *Phys. Status Solidi C*, vol. 14, no. 8, Art. no. 1600243, 2017.
[12] P. G. Whiting *et al.*, "Nanocrack formation in AlGaN/GaN high electron mobility transistors utilizing Ti/Al/ Ni/Au ohmic contacts," *Microelectron. Rel.*, vol. 70, pp. 41–48, Mar. 2017.
[13] K. Mori *et al.*, "Low-ohmic-contact-resistance V-based electrode for N-type AlGaN with high AlN molar fraction," *Jpn. J. Appl. Phys.*, vol. 55, no. 5S, 2016, Art. no. 05FL03.
[14] K. Singh *et al.*, "Formation of non-alloyed Ti/Al/Ni/Au low-resistance ohmic contacts on reactively ion-etched N-type GaN by surface treatment for GaN light-emitting diodes applications," *Appl. Phys. A*, vol. 125, Art. no. 24, Dec. 2018
[15] R.-H. Horng, H.-Y. Chien, F.-G. Tarntair, and D.-S. Wuu, "Fabrication and study on red light micro-LED displays," *J. Electron Devices Soc.*, vol. 6, no. 1, pp. 1064–1069, Aug. 2018.
[16] R.-H. Horng, H.-Y. Chien, K.-Y. Chien, W.-Y. Tseng, Y.-T. Tsai, and F.-G. Tarntair, "Development and fabrication of AlGaInP-based flip-chip micro-LEDs," *J. Electron Devices Soc.*, vol. 6, no. 1, pp. 475–479, Apr. 2018.
[17] P. Tian *et al.*, "Size-dependent efficiency and efficiency droop of blue InGaN micro-light emitting diodes," *Appl. Phys. Lett.*, vol. 101, no. 23, Art. no. 231110, Dec. 2012.

**SHUO-HUANG YUAN** received the B.S. degree in electrical engineering from Chinese Culture University, Taipei, Taiwan, in 2008, the M.S. degree in electrical engineering from National Ocean University, Keelung, Taiwan, in 2010, and the Ph.D. degree in electrical engineering from National Central University, Taoyuan, Taiwan, in 2016. From 2016 to 2019, he served as a Postdoctoral Fellow with the Department of Materials Science and Engineering, National Chung Hsing University. His major research focuses on optoelectronic devices and manufacturing process.

**SHIH-SIANG YAN** received the B.S. degree from the Department of Electrical Engineering, Ming Chi University of Technology, New Taipei City, Taiwan, in 2016, the M.S. degree from the Graduate Institute of Precision Engineering, National Chung Hsing University, Taichung, Taiwan, in 2018. His major research focuses on micro-LED design and process integration. He is currently an Engineer of Innolux Corp., Tainan, Taiwan.

**YU-SHIUAN YAO** received the B.S. degree from the Department of Materials Science and Engineering, I-Shou University, Kaohsiung, Taiwan, in 2017, and the M.S. degree from the Department of Materials Science and Engineering, National Chung Hsing University, Taichung, Taiwan, in 2019. His major research focuses on fabrication and optimization of passive-matrix red micro-LED displays.

**CHUNG-CHENG WU** received the B.S. degree from the Department of Materials Science and Engineering, I-Shou University, Kaohsiung, Taiwan, in 2017, and the M.S. degree from the Department of Materials Science and Engineering, National Chung Hsing University, Taichung, Taiwan, in 2019. His major research focuses on fabrication and optimization of passive-matrix blue micro-LED displays.

**RAY-HUA HORNG** (Fellow, IEEE) received the B.S. degree in electrical engineering from National Cheng Kung University, Tainan, Taiwan, in 1987, and the Ph.D. degree in electrical engineering from National Sun Yat-sen University, Kaohsiung, Taiwan, in 1993.

She is currently a Distinguished Professor with the Institute of Electronics, National Chiao Tung University, Hsinchu, Taiwan. Her current research interests include solid-state lighting devices, solar cells, power device, HEMT, flexible electronics, optoelectronics, nitride, and oxide semiconductor MOCVD growths.

**DONG-SING WUU** (Senior Member, IEEE) received the B.S., M.S., and Ph.D. degrees in electrical engineering from National Sun Yat-sen University, Kaohsiung, Taiwan, in 1985, 1987, and 1991, respectively.

From 2010 to 2016, he served as the President of Da-Yeh University. He is currently a Distinguished Professor with the Department of Materials Science and Engineering, National Chung Hsing University, Taichung, Taiwan. His current research interests include nitride- and oxide-based materials, optical devices, displays, and sensors.