Research Article Vol. 25, No. 3 | 6 Feb 2017 | OPTICS EXPRESS 2489
Optics EXPRESS

Fabrication of a vertically-stacked passive-matrix micro-LED array structure for a dual color display

CHANG-MO KANG,[1] DUK-JO KONG,[2] JAE-PHIL SHIM,[3] SANGHYEON KIM,[4] SANG-BAE CHOI,[1] JUN-YEOB LEE,[1] JUNG-HONG MIN,[1] DONG-JU SEO,[1] SOO-YOUNG CHOI,[1] AND DONG-SEON LEE,[1,*]

[1]*School of Electrical Engineering and Computer Science, Gwangju Institute of Science and Technology, 123 Cheomdangwagi-ro, Buk-gu, Gwangju 61005, South Korea*
[2]*Advanced Photonics Research Institute, Gwangju Institute of Science and Technology, 123 Cheomdangwagi-ro, Buk-gu, Gwangju 61005, South Korea*
[3]*Center for spintronics, Korea Institute of Science and Technology, 5, Hwarang-ro 14-gil, Seongbuk-gu, Seoul 02792, South Korea*
[4]*Center for Optoelectronic Materials and Devices, Korea Institute of Science and Technology, 5, Hwarang-ro 14-gil, Seongbuk-gu, Seoul 02792, South Korea*
**dslee66@gist.ac.kr*

Abstract: We report a color tunable display consisting of two passive-matrix micro-LED array chips. The device has combined vertically stacked blue and green passive-matrix LED array chips sandwiched by a transparent bonding material. We demonstrate that vertically stacked blue and green micro-pixels are independently controllable with operation of four color modes. Moreover, the color of each pixel is tunable in the entire wavelength from the blue to green region (450 nm - 540 nm) by applying pulse-width-modulation bias voltage. This study is meaningful in that a dual color micro-LED array with a vertically stacked subpixel structure is realized.

OCIS codes: (230.4000) Microstructure fabrication; (230.3670) Light-emitting diodes; (120.2040) Displays.

References and links

1. J. R. Bonar, G. J. Valentine, Z. Gong, J. Small, and S. Gorton, "High-brightness low-power consumption microLED arrays," Proc. SPIE **9768**, 97680Y1 (2016).
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. **99**(3), 031116 (2011).
3. G. Chen, M. Craven, A. Kim, A. Munkholm, S. Watanabe, M. Camras, W. Götz, and F. Steranka, "Performance of high-power III-nitride light emitting diodes," Phys. Status Solidi., A Appl. Mater. Sci. **205**(5), 1086–1092 (2008).
4. S. Pimputkar, J. S. Speck, S. P. DenBaars, and S. Nakamura, "Prospects for LED lighting," Nat. Photonics **3**(4), 180–182 (2009).
5. P. Tian, J. J. D. McKendry, Z. Gong, S. Zhang, S. Watson, D. Zhu, I. M. Watson, E. Gu, A. E. Kelly, C. J. Humphreys, and M. D. Dawson, "Characteristics and applications of micro-pixelated GaN-based light emitting diodes on Si substrates," J. Appl. Phys. **115**(3), 033112 (2014).
6. W. C. Chong, W. K. Cho, Z. J. Liu, C. H. Wang, and K. M. Lau, "1700 Pixels Per Inch (PPI) Passive-Matrix Micro-LED Display Powered by ASIC," in *2014 IEEE Compound Semiconductor Integrated Circuit Symposium* (CSICS, 2014), pp. 1–4.
7. X. Bao, J. Liang, Z. Liang, W. Wang, C. Tian, Y. Qin, and J. Lü, "Design and fabrication of AlGaInP-based micro-light-emitting-diode array devices," Opt. Laser Technol. **78**, 34–41 (2016).
8. M. Akhter, J. S. Lee, P. P. Maaskant, M. Rensing, N. Nudds, P. O. Brien, P. Degenaar, and B. Corbett, "A LED Micro-Display with 90×90 pixels on a 80 µm pitch," in *2015 European Microelectronics Packaging Conference* (EMPC, 2015), pp. 1–5.
9. Z. Liu, W. C. Chong, K. M. Wong, and K. M. Lau, "GaN-based LED micro-displays for wearable applications," Microelectron. Eng. **148**, 98–103 (2015).
10. S.-B. Shin, K.-I. Iijima, H. Okada, S. Iwayama, and A. Wakahara, "Design and Fabrication of Large Scale Micro-LED Arrays and Silicon Driver for OEIC Devices," IEICE Trans. Electron. **E95**, 898–903 (2012).

#282664 https://doi.org/10.1364/OE.25.002489
Journal © 2017 Received 12 Dec 2016; revised 21 Jan 2017; accepted 21 Jan 2017; published 31 Jan 2017

Optics EXPRESS

11. S. Zhang, S. Watson, J. J. D. McKendry, D. Massoubre, A. Cogman, E. Gu, R. K. Henderson, A. E. Kelly, and M. D. Dawson, "1.5 Gbit/s Multi-Channel Visible Light Communications Using CMOS-Controlled GaN-Based LEDs," J. Lightwave Technol. **31**(8), 1211–1216 (2013).
12. M. Funato, K. Hayashi, M. Ueda, Y. Kawakami, Y. Narukawa, and T. Mukai, "Emission color tunable light-emitting diodes composed of InGaN multifacet quantum wells," Appl. Phys. Lett. **93**(2), 021126 (2008).
13. Y. J. Hong, C. H. Lee, A. Yoon, M. Kim, H.-K. Seong, H. J. Chung, C. Sone, Y. J. Park, and G.-C. Yi, "Visible-color-tunable light-emitting diodes," Adv. Mater. **23**(29), 3284–3288 (2011).
14. Y. Tchoe, J. Jo, M. Kim, J. Heo, G. Yoo, C. Sone, and G.-C. Yi, "Variable-Color Light-Emitting Diodes Using GaN Microdonut Arrays," Adv. Mater. **26**(19), 3019–3023 (2014).
15. Y. F. Cheung and H. W. Choi, "Color-Tunable and Phosphor-Free White-Light Multilayered Light-Emitting Diodes," IEEE Trans. Electron Dev. **60**(1), 333–338 (2013).
16. K. N. Hui, X. H. Wang, Z. L. Li, P. T. Lai, and H. W. Choi, "Design of vertically-stacked polychromatic light-emitting diodes," Opt. Express **17**(12), 9873–9878 (2009).
17. W. Hou, C. Stark, S. You, L. Zhao, T. Detchprohm, and C. Wetzel, "Evaluation of metal/indium-tin-oxide for transparent low-resistance contacts to p-type GaN," Appl. Opt. **51**(23), 5596–5600 (2012).
18. S.-I. Park, Y. Xiong, R.-H. Kim, P. Elvikis, M. Meitl, D.-H. Kim, J. Wu, J. Yoon, C.-J. Yu, Z. Liu, Y. Huang, K. C. Hwang, P. Ferreira, X. Li, K. Choquette, and J. A. Rogers, "Printed assemblies of inorganic light-emitting diodes for deformable and semitransparent displays," Science **325**(5943), 977–981 (2009).

1. Introduction

Many research groups and companies are interested in micro light emitting diodes (micro-LEDs) because they are suitable candidates for next-generation displays such as smart glasses, head mounted displays (HMDs), and head up displays (HUDs). When compared to organic LEDs (OLEDs) or liquid crystal displays (LCDs), which are conventionally used as light sources for displays, inorganic LEDs have many advantages such as low power consumption, high brightness, short response time, and long lifetime [1–4].

Although inorganic LEDs have many advantages, it is still challenging to realize a red-green-blue (RGB) color controllable light source from one chip for a high-resolution micro-LEDs display. Many studies on micro-LEDs for application to optical communication or displays have been reported, but the developed LEDs have been limited to one color light source [5–11]. An epitaxially grown inorganic LED structure only has monochromatic light emission and requires that the fabricated red, green, and blue chips be separately arranged for full color emission. Meanwhile, laterally arranged RGB LED chips are mostly used at present. However, a lateral arrangement of red, green, and blue LED chips requires three times larger space compared with configuring each alone in a single package and thus reduction of the chip size and integration techniques are required. Therefore, an innovative solution for achieving a high-resolution full color micro-LED display is needed.

Many epitaxial structures and fabrication methods have been suggested to realize various color emissions from a one-pixel LED. Some research groups have introduced InGaN/GaN nanorods or micro pyramid LED structures and demonstrated blue to red light emission by changing the current injection density [12–14]. One notable development is that light emission color can be varied from an epitaxially grown wafer having nano- or microstructure. However, these nano- or microstructures require complex growth techniques and have inevitable epi-variation that it is difficult to commercialize for industrial use. Furthermore, it is difficult to independently control the brightness and color of the light emitted from each nano- or microstructure. Although we can vary the applying current injection density, the current path is not controllable and the effective current density toward each nano- or microstructure is consequently different.

As another approach, a few research groups have realized various light emission colors from one-pixel position by vertically stacking RGB LED chips [15, 16]. Although this structure can cover the full colors in one pixel, it is not easily applied to displays due to the difficulty in addressing each pixel. Metallization, wiring, and connection with the driver circuit have to be carefully considered for color tunable pixel LEDs.

In this study, we demonstrated a vertically-stacked passive-matrix micro-LED array structure that can independently address many green subpixels and blue subpixels. In addition, the color of each pixel can be covered in the entire wavelength from the blue to

Optics EXPRESS

green region (450 nm - 540 nm) by applying a pulse-width-modulated (PWM) voltage. In particular, this technique does not require laterally arranged subpixels by vertically stacking a micro-pixel LED array. For this reason, it is applicable to displays with high resolution. To realize this structure, we adopted passive-matrix addressing and a wafer bonding technique.

2. Experiment

We fabricated a vertically-stacked passive-matrix micro-LED array structure. Figure 1(a) illustrates the fabrication steps of the vertically-stacked passive-matrix micro-LED array. We used conventional blue and green LED epistructures grown on a double-side-polished (DSP) sapphire substrate. The blue and green LED epitaxial layer consists of *p*-GaN, InGaN/GaN multi quantum well (MQW), and *n*-GaN.

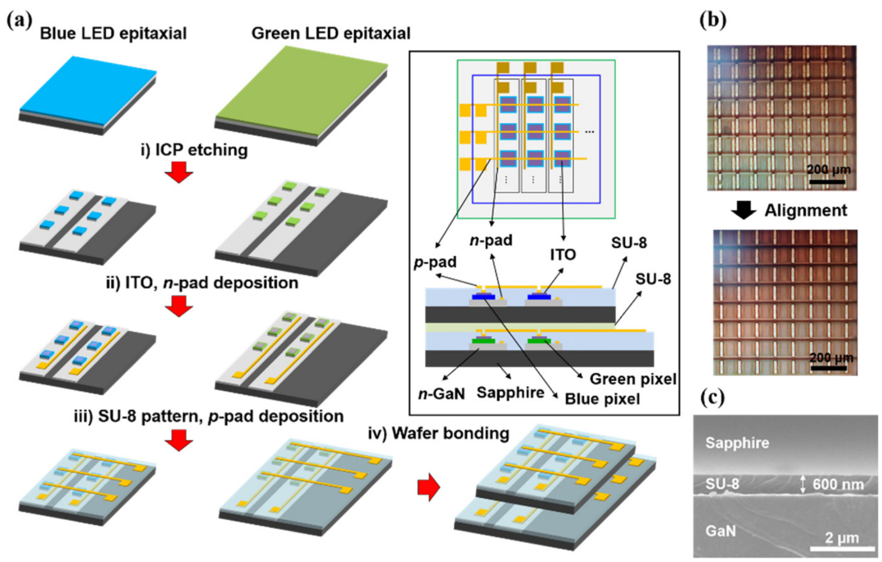

Fig. 1. (a) The fabrication steps of a vertically-stacked passive-matrix micro-LED array: i) ICP etching of GaN for the formation of the row and all pixels of the micro-LED array, ii) deposition of ITO on *p*-GaN, deposition of Ti/Au layers on *n*-GaN, iii) SU-8 pattern for isolation between metal electrodes, deposition of Cr/Au layers, iv) wafer bonding of the blue and the green LED chip. (b) Microscopy images before (top) and after (bottom) alignment of the blue LED chip stacked on green LED chip. (c) SEM image of the cross-sectional interface between the blue and the green LED chip.

First, to separately operate each blue-LED pixel connected by a cross metal line, all rows of the micro-LED array should be electrically isolated. This isolation was realized by etching a 6 µm thick GaN down to the sapphire substrate by inductively coupled plasma (ICP) etching. Subsequently, to define all pixels of the blue micro-LED array and expose the *n*-GaN for *n*-type electrode formation, a standard photolithography process and ICP etching were implemented. Here, the pixel size, the pixel pitch, and the pixel etching depth are 75 × 75 µm^2, 100 µm, and 700 nm, respectively [Fig. 1. (a)- i]. An indium tin oxide (ITO) layer was deposited on top of the pixels for current spreading and *p*-type ohmic contact. After deposition of the ITO layer, the blue LED chip was annealed at 600°C for 5 min via rapid thermal annealing to form ohmic contact. Ti/Au stripe pads were then deposited on the *n*-type GaN to form a common cathode electrode [Fig. 1. (a)- ii]. To electrically isolate the *n*-type electrodes from the *p*-type electrodes, which are deposited later, a SU-8 photoresist was deposited by a spin coater and contact hole patterns for opening the *p*-type ohmic contacts were formed by a photolithography process. The *p*-type ohmic contacts of the blue micro-LED array in the same column were then connected with Cr/Au stripe pads for common anode electrodes. From the above process, a blue passive-matrix micro-LED array, which

Optics EXPRESS

would be located on the upper part of the final device, was fabricated [Fig. 1. (a)- iii]. Likewise, the green passive-matrix micro-LED array, which would be located in the lower part of the final device, was fabricated by the same process as the blue passive-matrix micro-LED array. However, the chip and the metal stripe pads of the green passive-matrix micro-LED array were designed with bigger size than those of the blue passive-matrix micro-LED array to access all metal contacts of the final device when the blue and the green LED chip were vertically stacked. The size of the blue and the green LED chip is 0.8 × 0.8 cm^2 and 1.2 × 1.2 cm^2, respectively. Before wafer bonding of the fabricated blue and green micro-LED arrays, each pixel has to be accurately aligned in the vertical direction. Figure 1(b) shows microscopy images before and after alignment of the blue LED chip stacked on the green LED chip. Finally, we bonded two chips by using a transparent bonding material (SU-8) through a 250°C thermal process under 1 kg/cm^2 pressure [Fig. 1. (a)- iv]. The thickness bonded by SU-8 was only 600 nm and it shows a uniform interface without any defects, as shown in the SEM image of Fig. 1(c). Top and cross-section images of the final device are shown in the inset of Fig. 1(a).

3. Results and discussion

We measured the transmittance of the fabricated 8 × 8 micro-LED array. The transmittance is an important factor for light emission because each pixel (blue and green micro pixel LEDs) is vertically stacked and we also have to consider transmittance loss from the bonding material layer. In Fig. 2(a), the micro-LED array has approximately 63% transmittance for the visible spectrum and the transmittance has an oscillation around 63% due to the interference phenomena occurring in the optically thin layer [17]. The factor that most strongly influences the transmittance of the micro-LED array is the area covered by the metal line. The ratio occupied by the metal in the display area is 20%, as calculated in Table 1. Briefly, this means that the micro-LED array has about 20% loss of transmittance due to opaque metal lines. In addition to metal lines, light absorption at the ITO and SU-8 layers further reduces the transmittance of the micro-LED array. There are possible solutions to improve the transmittance of the fabricated micro-LED array to a level higher than 63%: i) optimization of the design of the stripe metal line, ii) enhancing the transmittance of the spreading layers and the bonding layer, iii) and decreasing the thickness of the DSP sapphire substrates.

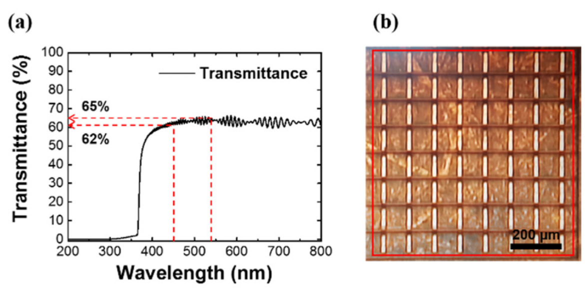

Fig. 2. (a) Transmittance of the fabricated 8 × 8 micro-LED array structure. (b) Microscopy image of the 8 × 8 micro-LED array involving line metals.

Table 1. Specifications of metal electrodes in the 8 × 8 micro-LED array.

	Width	Length	Number	Area
8 × 8 micro-LED array	800 µm	800 µm	1	640000 μm^2
p-metal line	15 µm	800 µm	8	96000 μm^2
n-metal line	5 µm	800 µm	8	32000 μm^2
Cross of two metal lines	15 µm	5 µm	64	4800 μm^2
Fill factor of the metal lines	20%			

We measured the optical properties of the fabricated device by four color modes using four probes. The four color modes are as follows: i) only blue emission, ii) only green

Optics EXPRESS

emission, iii) blue and green emissions at different pixel positions, iv) blue and green emissions at the same pixel position. Here, we denote the pixel in the i-th row and the j-th column of the 8 × 8 micro-LED array as M (i, j) for convenience. In the case of the blue and the green micro-LED array, we indicate the blue subpixel and the green subpixel as M_B (i, j) and M_G (i, j) respectively. Figure 3 shows microscopy images and electroluminescence (EL) spectra measured by the four color modes. In the blue only emission mode, voltage was applied to M_B (1, 2) of the blue LED array, which is located in the upper part of the fabricated device, to address only a blue subpixel at M (1, 2) of the micro-LED array. As shown in Fig. 3(a), only blue light was emitted at M_B (1, 2) of the micro-LED array and the EL spectrum shows only a peak wavelength of 450 nm. In the green only emission mode, voltage was applied to M_G (1, 2) of the green LED array, which is located in the lower part of the fabricated device, to address only a green subpixel at M (1, 2) of the micro-LED array. Here, the blue and the green LED chips are fabricated on transparent DSP sapphire and light absorption at the sapphire substrate is negligible. Furthermore, the photon energy of the green light emitted from the green subpixel is lower than the energy bandgap of the active region of the blue subpixel. Therefore, photons of green light pass through the blue subpixel of the upper chip vertically. As a result, only green light was emitted at M_G (1, 2) of the micro-LED array and the EL spectrum of the micro-LED array has only a peak wavelength of 540 nm, as shown in Fig. 3(b). Next, to confirm the simultaneous emission of both blue and green light at different pixel positions, voltage was applied to M_B (1, 2) and M_G (3, 2) at the same time. As shown in Fig. 3(c), blue light was emitted at M_B (1, 2) and green light was emitted at M_G (3, 2), thus demonstrating simultaneous emission at different pixel positions. As expected, the EL spectrum of the micro-LED array has two peaks wavelength of 450 nm and 540 nm. Finally, in the blue and green emission modes at the same pixel position, voltage was applied to M_B (1, 2) and M_G (1, 2) at the same time, to address both the blue subpixel and the green subpixel at M (1, 2) of the micro-LED array. Cyan light was emitted at M (1, 2) by mixing the blue light emitted at M_B (1, 2) and the green light emitted at M_G (1, 2), as shown in Fig. 3(d). The EL spectrum of the micro-LED array shows wavelength with two peaks of 450 nm and 540 nm. The dual emission at the same pixel position demonstrates the potential of the vertically-stacked micro-LED array for high resolution because the micro-LED array prepared using this technique does not require laterally arranged subpixels. Through four color modes, we demonstrated that both green subpixels and blue subpixels can be controlled independently at any pixel position.

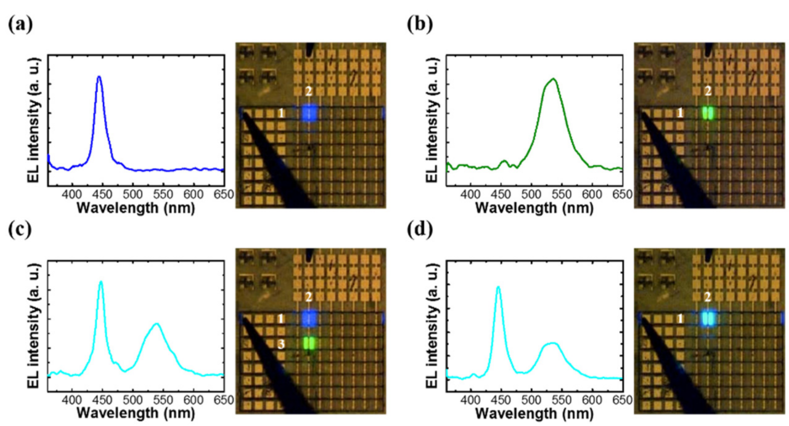

Fig. 3. The EL spectrum and microscope image of (a) only blue emission, (b) only green emission, (c) blue and green emission at different pixel positions, (d) blue and green emission at the same pixel position.

Research Article | Vol. 25, No. 3 | 6 Feb 2017 | OPTICS EXPRESS 2494

In addition to the color combination with monochromatic blue (~450 nm) and green (~540 nm) emission, we can control the whole wavelength from the blue to green region from one pixel by changing the duty ratio of the PWM voltage bias. The duty ratio is defined as the percentage of one period in which a signal is active and can be expressed as Eq. (1) below:

$$Duty\,ratio = \frac{t_{on}}{t_{on} + t_{off}} \tag{1}$$

where t_{on} and t_{off} are the duration in which a signal is active and non-active, respectively. We measured CIE coordinators and EL spectra by changing the duty ratio of PWM for the blue and the green subpixels at M (1, 2) of the micro-LED array. For comparison of the blue subpixel and the green subpixel, PWM voltage was applied to one subpixel and fixed DC voltage was applied to another subpixel. Here, the PWM frequency is 300 Hz. Figure 4(a) shows the EL spectra measured by changing the duty ratio for the green subpixel. As the duty ratio of the green subpixel decreases, the spectrum approaches that of the blue peak (~450 nm) dominant emission. While decreasing the duty ratio of the blue subpixel, the spectrum approaches that of the green peak (~540 nm) dominant emission, as shown in Fig. 4(b). This means that the color of the pixel can be tunable to blue or green dominant color. The number of colors that can be produced in one pixel is determined by a combination of the PWM of the blue subpixel and the green subpixel. For example, if the blue subpixel and the green subpixel are controlled by PWM with N-bit and M-bit, respectively, the number of colors made in one pixel is calculated to be $2^{(M + N)}$. Eventually, the color of one pixel in the device can cover from blue to green by various duty ratios of the PWM. The CIE coordinates and the microscope images in Figs. 4 (c) and (d) show the color changes from green to the blue at M (1, 2) of the micro-LED array. From these results, we demonstrated that the fabricated device has many possibilities for display application with high resolution as various colors can be selected in the same pixel position.

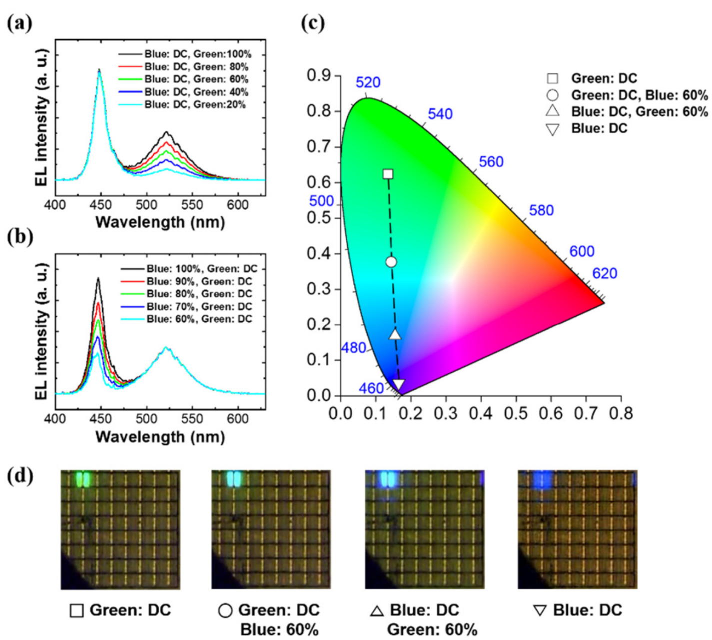

Fig. 4. The EL spectra measured by changing the duty ratio of PWM for (a) green subpixel and (b) blue subpixel. (c) CIE 1931 x-y chromaticity diagram of the device by various PWM voltages. (d) Series of microscope images at M (1, 2) of the micro-LED array applied to various PWM voltages.

Optics EXPRESS

The next step to this study must be a realization of full color displays by adding ‘red’ color. We recognize that many research groups make great efforts to realize full color displays. In order to realize the full color display as well as the dual color display, we have to consider the passive-matrix micro-LED array using AlGaInP-based red LEDs. However, using the red LEDs have two problems such as conductivity and opacity of the substrate.

Unlike blue and green LEDs that use nonconductive sapphire substrates, the red LEDs typically use conductive GaAs substrates. It is difficult to implement a passive-matrix display in the case of conductive GaAs substrates due to the electrical isolation between the rows of the display. As a result, the pixels of the display cannot be controlled independently. There are possible solutions to electrically isolate the rows of the display: i) bonding red LEDs on a nonconductive substrate, ii) making the GaAs substrate semi-insulating, iii) or etching down to the backside of the GaAs substrate. Many research groups have implemented the red passive-matrix display in a variety of methods [7, 18]. It shows the possibility to realize the full color display.

Another problem caused from the red LEDs is comparative low transmittance. Due to the opacity of the GaAs substrate, there are difficulties regarding to transparent display applications with red LEDs. For the transparent display, it is required to remove the GaAs substrate and fabricate the red passive-matrix display on the transparent substrates. Despite the removal of the substrate, the low transmittance of the pixel itself is inevitable. However, the vertically-stacked subpixel structure can improve the transmittance of the display. It is because the vertically-stacked subpixel structure can expand the transparent area and reduce the emission area of the display more than the laterally arranged subpixel structure with same resolution. As a result, the vertically-stacked subpixel concept has the possibility of realizing transparent full color display.

4. Conclusion

In this study, we fabricated a dual color micro-LED array that can independently control both green subpixels and blue subpixels at any position. Interestingly, the color at the same pixel position is tunable from green to blue wavelength under various PWM voltages. The device is suitable for a micro-LED display with high resolution because the micro-LED array with this technique does not require laterally arranged subpixels. In addition, the micro-LED array has transmittance as high as 63%. These remarkable results show the outstanding potential of the proposed micro-LED display for numerous display applications, such as smart glasses, HMDs, and HUDs, which require high resolution, low power consumption, and transparent properties.

Funding

Ministry of Trade Industry and Energy (MOTIE) (10067424); Gwangju Institute of Science and Technology (GIST) (GN2016-05).

Acknowledgments

We thank Jae-Phil Shim and Sanghyeon Kim for helpful discussions.