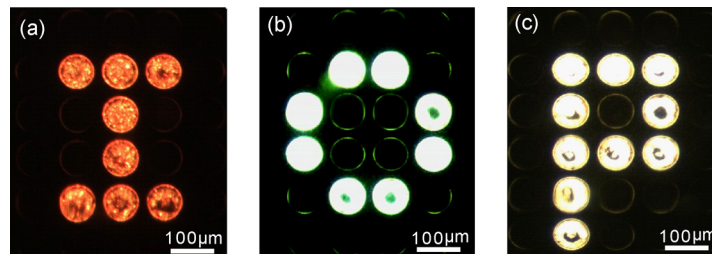


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Abstract: We demonstrate a color-tunable smart display system based on a micropixelated light-emitting diode (μ LED) array made from one InGaN epitaxial structure with high (0.4) indium mole fraction. When integrated with custom complementary metal–oxide–semiconductor (CMOS) electronics and a CMOS driving board with a field-programmable gate array (FPGA) configuration, this μ LED device is computer controllable via a simple USB interface and is capable of delivering programmable dynamic images with emission colors changeable from red to green by tailoring the current densities applied to the μ LED pixels. The color tunability of this CMOS-controlled device is attributed to the competition between the screening of piezo-electric field and the band filling effect. Comparable brightness of the μ LED pixels emitting at different colors was achieved by adjusting the duty cycle. Further measurement suggests that this microdisplay system can also be used for high-speed visible light communications.

Index Terms: Complementary metal–oxide–semiconductor (CMOS), InGaN, microlight-emitting diodes (μ LEDs), color tunability, microdisplay, visible light communications (VLC).

1. Introduction

High-performance III-Nitride light-emitting diodes (LEDs) have achieved great success in a variety of areas such as signaling, displays, and solid-state lighting [1]–[4]. For such purposes, inorganic LEDs have attractions over conventional liquid crystal technology and organic LEDs (OLEDs), such as high efficiency and brightness, high reliability and stability, and the capability to operate under harsh temperature conditions [5], [6]. However, compared with liquid crystal technology and OLEDs [6]–[9], conventional thin-film inorganic LEDs fabricated from the same epilayer usually emit light at a single color determined by the specific quantum-well (QW) structure used. Such monochromatic emission limits the multicolor applications of these LEDs. Recent progress toward multicolor

application of inorganic LEDs, such as flat panel screens for television, computer, and mobile devices, therefore mainly relies on the mechanical packaging together of separate LED devices emitting at different colors to form a multicolor unit. However, this method imposes a major limitation for the scalability and the resolution of the display as a result of the limited packaging placement accuracy (a few hundred microns). It is expected that the packaging approach will become increasingly difficult with decreasing LED die size and increased packaging density. A multicolor microdisplay based on micropixelated LEDs (μ LED) with typical pixel sizes of 20 μm , for example, would therefore be very difficult to achieve by this technology. Alternatively, the integration of monochromatic LEDs with different color converters such as organic polymer blends and semiconductor nanocrystals has also been reported [10], [11]. However, the addition of color converters complicates the device fabrication and may reduce the device reliability due to the degradation of integrated color converters. Therefore, to simplify the fabrication complexity associated with aforementioned techniques, it is extremely important to explore simpler approaches for multicolor displays.

There have been several reports on different growth methods to achieve color tunability of inorganic LEDs and their potential in multicolor display and phosphor-free white lighting [12]–[14]. However, to the best of our knowledge, no multicolor inorganic display system has been realized based on these LED wafer materials. Here, we demonstrate a complementary metal–oxide–semiconductor (CMOS) controlled inorganic microdisplay system capable of delivering programmable animated images while showing direct color tuning from red to green at comparable output powers, all based on one InGaN structure. To implement the microdisplay system, we fabricate a dedicated micropixel LED array from this InGaN structure, interface it to a CMOS driver array, and show direct display performance and color tuning under the CMOS control. Our InGaN material contains high (0.4) indium mole-fraction quantum wells, and we have recently reported the physics of color tuning in this material [15]. Further measurement shows that the modulation bandwidth of these integrated CMOS/ μ LED tunable pixels reaches 100 MHz, thus also providing a wavelength-agile source for high-speed visible light communications (VLC). Error-free data transmission at bit rates of up to 250 Mbit/s per pixel has been achieved using on–off key (OOK) nonreturn-to-zero (NRZ) modulation.

2. Device Design and Fabrication

2.1. LED Wafer Structure and μ LED Fabrication

The LED wafer used for the microdisplay fabrication was grown on a (0001) sapphire substrate by metal organic chemical vapor deposition. The epitaxial structure consists of a 1.5- μm -thick GaN buffer layer, a 4- μm -thick n-doped GaN layer, a five-period $\text{In}_{0.18}\text{Ga}_{0.82}\text{N}$ (3 nm)/GaN (10 nm) multi-QW layer emitting at 460 nm, a five-period $\text{In}_{0.4}\text{Ga}_{0.6}\text{N}$ (2.5 nm)/GaN (12 nm) multi-QW layer emitting at 600 nm (main QWs), and a 210-nm-thick p-GaN cap layer. The low-indium-content blue QWs function as an electron reservoir and prestrain-relaxation layer for improving the radiative efficiency of the main QWs [16], [17]. The μ LED device used for the microdisplay demonstration was fabricated by using a similar process to that previously reported [18]. It consists of a 16×16 array of individually addressable microdisk LED pixels with a diameter of 72 μm on a 100- μm center-to-center pitch [see Fig. 1(a)]. Each pixel within the μ LED array shares a common n-contact and is addressed via an individual p-contact. Due to the flip-chip design, light is extracted through the polished sapphire substrate of the device. Fig. 1(b) shows the current–voltage (I – V) and corresponding optical power versus driving current (L – I) curves of a typical such LED pixel, driven by CMOS under dc conditions at room temperature.

2.2. CMOS Fabrication and Function

The CMOS driver chip, which consists of a 16×16 array of individually controllable $100 \times 100 \mu\text{m}^2$ driver cells on a center-to-center pitch of 100 μm , was designed to match the $16 \times 16 \mu$ LED array. To achieve electrical connection between the entire μ LED array and the CMOS driver chip, each μ LED pixel's p-pad is Au-bump bonded onto a corresponding CMOS driver cell, which contains

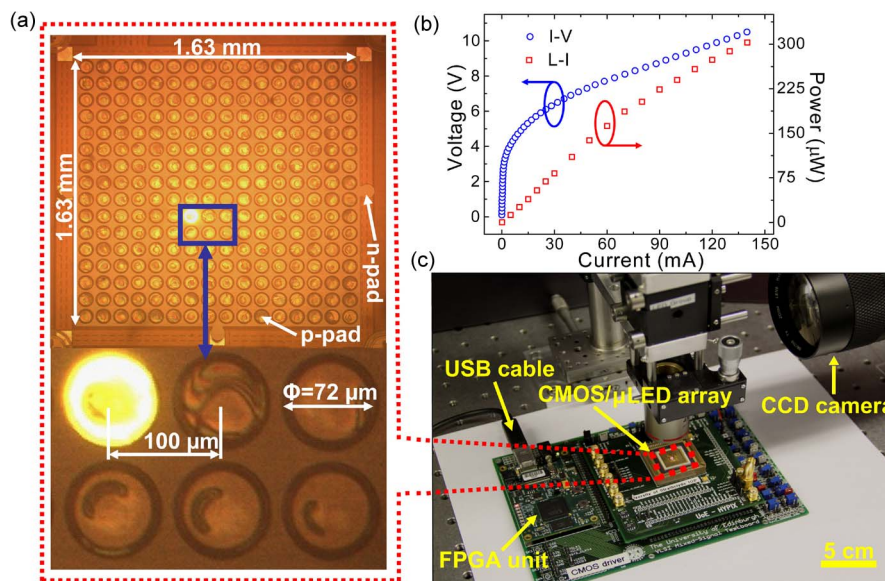


Fig. 1. (a) Microscope image of the whole CMOS-bonded μ LED array with an individual pixel in operation. (b) Characteristic I - V and L - I curves of a $72\text{-}\mu\text{m}$ -diameter CMOS-bonded μ LED pixel. (c) Image of the CMOS driving board and relevant microscope/CCD-camera setup for microdisplay demonstration.

a $60 \times 60 \mu\text{m}^2$ bonding pad and dedicated logic circuit. Each bonded CMOS driver functions as a high-speed switch to control the output of each LED pixel according to the state of input trigger signal. When the input trigger signal of a CMOS cell is logic 1, the CMOS driver is turned on and the output of the corresponding μ LED is determined by the applied voltage and the I - V and L - I characteristics of the μ LED itself. Thus, by programming the input trigger signals for each CMOS driver cell, this CMOS/ μ LED microdisplay system is capable of delivering dynamic images. To implement this, a CMOS driving board [as shown in Fig. 1(c)] with a field-programmable gate array (FPGA) unit and a simple computer interface was developed. The FPGA unit allows the μ LED array to deliver video images by distributing input signals for CMOS drivers according to the computer instructions programmed by hardware description language and also powers the whole microdisplay system using the power supplied from a computer USB port. More details about the design, function, and operation procedures of the CMOS electronics used here can be found in our previous reports [19], [20]. In this paper, dynamic images at a frame rate of 1.67 Hz (0.6 s per frame) are shown. (Relevant video can be found in the supplemental materials.) The current CMOS chip can only update the μ LED pixels one by one, which limits the frame rate. But we anticipate that, with a suitable software interface and a specifically designed CMOS chip, which could update pixels an entire row at a time, dynamic video could be displayed at high enough frame rates (≥ 24 frames per second) for this microdisplay system.

3. Experimental Details and Results

Fig. 2 shows the current-dependent electroluminescence (EL) spectra of a typical CMOS-controlled μ LED pixel, under different dc injection currents at room temperature. A significant blueshift of the emission wavelength of the main QWs [as indicated by the arrow of Fig. 2] is observed as the injection current is increased. Both the screening of the quantum-confined Stark effect (QCSE) in polar QWs and the band-filling effect can lead to this blueshift. Based on the numerical stimulation results reported [15], in the relatively low-current-density regime ($< 3.5 \text{ kA cm}^{-2}$), the main contribution to the blueshift of the main QWs is due to the band filling effect and the screening of the QCSE, whereas in the high-current-density regime, the blueshift of the spectra is mainly caused by the band filling effect, since the piezo-electric field is almost completely screened in the

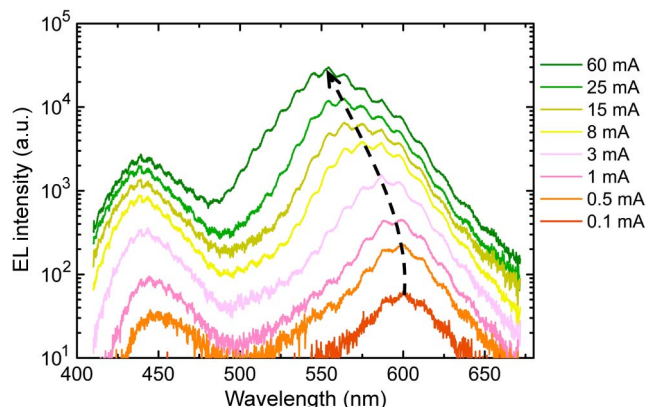


Fig. 2. EL spectra of the color-tunable CMOS/ μ LED pixel taken at various injection currents from 0.1 to 60 mA.

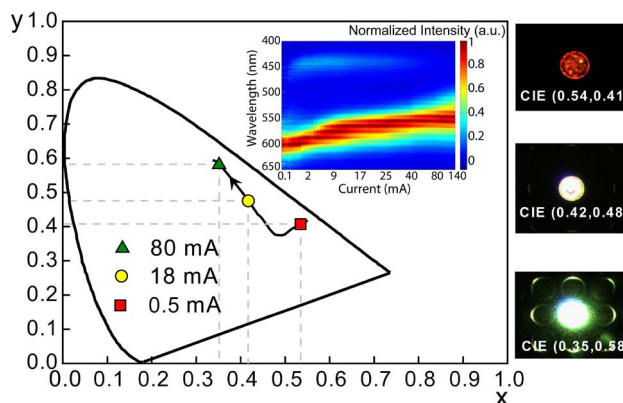


Fig. 3. Chromatic coordinate curve corresponding to the normalized EL spectra shown in the inset, with three specific chromatic coordinates highlighted. The three μ LED images are related to the highlighted chromatic coordinates. Inset: current-dependent (from 0.1 mA to 140 mA) normalized EL spectral mapping of the μ LED array.

high-current-density regime. Shown in the inset of Fig. 3 is a detailed current-dependent normalized EL spectral mapping. It can be seen that the main emission peak wavelength of the μ LED shifts from 600 nm to 550 nm when increasing the injection current from 0.1 mA to 80 mA and saturates at 550 nm. The dominant emission of the μ LED is from the main QWs, whereas the emission from the blue QWs is (as it is designed to be) much weaker, which is probably due to the long hole-migration distance between the blue QWs and the p-GaN layer [21]. Fig. 3 shows the calculated CIE (1931) coordinate curve according to the current-dependent normalized EL spectra. As shown in Fig. 3, the CIE coordinate curve shifts from the red region to the green region with increased injection current, indicating a distinct and direct color change of the light emitted by the μ LED. Three μ LED images with different colors, corresponding to the three CIE coordinates highlighted in Fig. 3, are shown in the same figure as well.

A current-dependent spectral shift is generally undesirable for applications where a constant emission wavelength is required. However, utilizing this characteristic of the μ LEDs, it is feasible to demonstrate a color-tunable or multicolor microdisplay system based on a single LED array made from the same wafer material. Such a multicolor display system has many advantages such as the elimination of using inorganic/organic color converters and LED dies emitting at other colors, thereby reducing the production cost and enabling a more compact design. Furthermore, there is the possibility to use color mixing to increase the color gamut of the microdisplay, by cycling

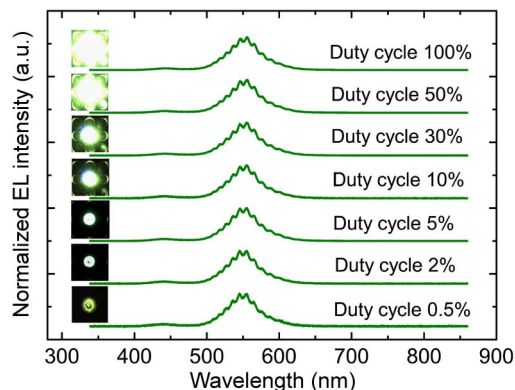


Fig. 4. Duty-cycle-dependent EL spectra of the μ LED, with relevant images shown in the same figure as well.

individual pixels through different colors at fast rates. However, one should note that, to achieve this multicolor display, the current within each pixel must be varied if each pixel is under CW operation, which in turn induces a strong brightness variation for the display. Knowing that the apparent average brightness of each pixel under pulsed operation can be tuned by changing the duty cycle, specifically designed active CMOS driver electronics have been used to drive the LED array. In other words, comparable brightness of the μ LED emitting at different colors is achieved by adjusting the duty cycle of the working μ LED pixel by sending appropriate trigger signals to the CMOS drivers. To control the state of μ LED using an external source, the trigger signal should be first adjusted to reach the logic threshold of the CMOS electronics and then sent to the CMOS chip to modulate the CMOS drivers directly. In this case, all the working μ LED pixels, originally turned on under CW operation, will follow the trigger signal. The trigger signal used here is a square wave with a peak-to-peak voltage of 2 V and a period of 20 ms (frequency of 50 Hz). Its duty cycle is adjustable, and using this pulsewidth modulation to normalize the power of μ LED pixels emitting at different colors does not influence the capability of the microdisplay to deliver animated images. Plotted in Fig. 4 is the duty-cycle-dependent EL spectra of the μ LED, with a peak-to-peak current of 80 mA. The apparent “glow” seen from the adjacent pixels of the inset images is due to light scattering from the pixel sidewalls. As shown in Fig. 4, the brightness of the μ LED is increased, while the emission wavelength is slightly redshifted with increasing the duty cycle. The redshift of the spectra is attributed to the self-heating induced bandgap shrinkage when the duty cycle is large. Nevertheless, the redshift is so small that the brightness of the display can be controlled mainly by adjusting the duty cycle without changing the color dramatically. In other words, the change of color caused by the small redshift is not noticeable by the human eye and is thus not a real problem for the microdisplay. This is very important for the multicolor demonstration when the μ LED is operated at different colors with comparable brightness. The reason that changing the brightness of the μ LED without changing its color significantly is due to the short turn-on and turn-off time of the μ LED (ns regime) [22], which ensures the peak current remains basically the same when the μ LED is turned on regardless of the duty cycle. The same results were also observed when the μ LED is operating at lower current levels. In the duty-cycle-dependent EL measurement, the μ LED device was driven at long enough time to reach stable EL emission at each duty cycle, and we repeated this measurement three times. Each measurement took about one hour, and we did not observe any obvious redshift at higher duty cycle in each measurement. There are two possible reasons to explain why the redshift is very small for our devices. First, the screening of QCSE and the band-filling effect always dominate the emission of the main QWs of this high-indium content material [15]. Second, the superior ability of heat dissipation of this CMOS-bonded μ LED device will induce smaller thermal effect on its EL spectra, the μ LED pixel approach has been proved to have better performance in heat dissipation than its broad area counterpart [23], and the metal bump bonded on the p-pad of each μ LED pixel could also help it to dissipate heat when the pixel is in operation.

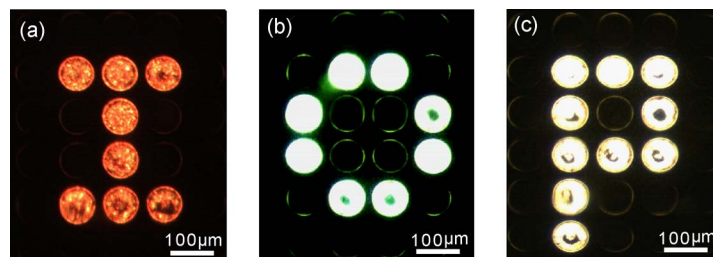


Fig. 5. Controllable emission pattern “IOP” (abbreviation for the Institute of Photonics) generated by the CMOS-controlled μ LED array.

Shown in Fig. 5(a)–(c) are representative emission patterns at red, green and yellow wavelengths generated by the CMOS-controlled μ LED array. Approximately identical average output power for each pattern was achieved by driving the μ LED array with different duty cycles. The red pixel is in dc operation at 0.5 mA with an output power of $0.93 \mu\text{W}$, the green pixel is in operation under 0.5% duty cycle at 80 mA with an output power of $1.03 \mu\text{W}$, and the yellow pixel is in operation under 2% duty cycle at 18 mA with an output power of $0.97 \mu\text{W}$. As shown in Fig. 5, all the emission patterns had uniform color distribution across the working pixels. Furthermore, the μ LED pixels have also shown good output and EL uniformity at different current densities [15]. Due to the power normalization along with the small pixel size used, the absolute power from individual μ LED pixels is relatively low here compared with commercial illumination LEDs. However, in this case, the power density per pixel still reaches 25.6 mW cm^{-2} , which is enough for practical applications such as head-mounted displays and contact lens displays [7], [24]. According to our reliability test for a similar μ LED device, its pixel does not show any obvious degradation of power output (less than 5%) for 2200 hours under CW operation with an injection current of 20 mA.

Apart from being useful for multicolor displays, further measurement shows that the CMOS-controlled μ LED pixels have high modulation bandwidth, indicating that they can also be used for optical data transmission. The idea is to utilize this CMOS-controlled smart display to deliver programmable animated images for the purpose of display and, at the same time, modulate one pixel or several of them for the purpose of data communications. Such a smart display system could show dynamic images to the human eye but have additional information encoded in them, which can be received by a detector to set up an optical-communication link, e.g., implemented in a cellphone format. Fig. 6(a) shows the frequency response for a typical μ LED pixel with a total applied bias of 6.5 V. Optical -3-dB bandwidth of the μ LED pixel was found to be approximately 100 MHz, and the drop in the frequency response seen at 450 MHz has been attributed to the CMOS drivers not being able to modulate their output in response to signals at these high frequencies. A detailed investigation of the frequency response of other CMOS-bonded μ LED devices and the corresponding method to fit the frequency response curve has been reported earlier [20]. The CIE coordinates at 6.5 V bias are (0.37, 0.54) when driven under dc conditions. At increasing modulation frequency, the color changes slightly, which is attributed to a reduction in the effective voltage applied to the μ LEDs due to the frequency response characteristics of the CMOS/ μ LED pixels; however, at bit rates above 50 Mbit/s, the color coordinates remain fairly stable at (0.39, 0.53). This change in color during modulation could be mitigated in a future CMOS design by implementing a small-signal modulation scheme, rather than an OOK scheme as shown in this work. Data transmission was carried out using an individual pixel from the μ LED array based on a bit-error rate test system (BERT). The data pattern output from the BERT was OOK-NRZ pseudorandom binary sequence with a standard pattern length of $2^7 - 1$ bits and a peak-to-peak voltage swing of 2 V. The data signal from the BERT reaches the logic threshold of the CMOS electronics so that it can be used to trigger the CMOS drivers directly and, in this way, modulate the μ LED pixel. The optical signal from the modulated pixel was incident on a high-speed silicon photodetector, and the electrical output from this detector was sent to a 25-dB amplifier before returning to the BERT. In this case, error-free data transmission, defined as a bit error ratio of less than 1×10^{-10} , could be achieved for bit rates of

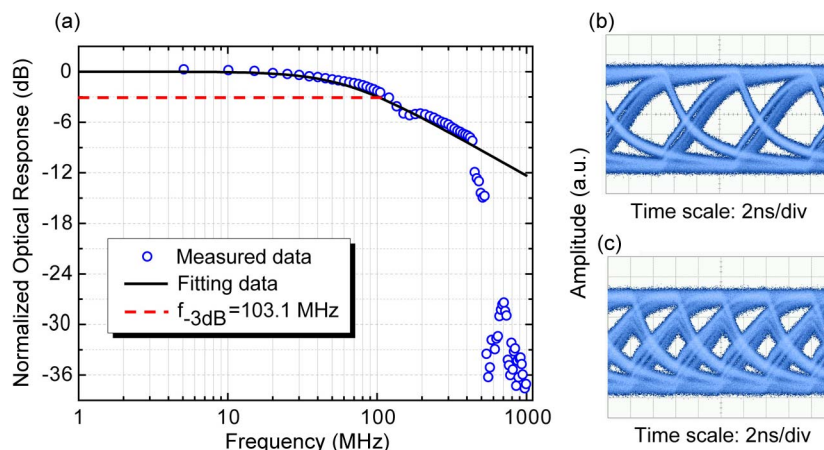


Fig. 6. (a) Frequency response curve of a typical 72- μm diameter CMOS/ μLED pixel, with a forward bias of 6.5 V, and eye diagrams taken at (b) 155 and (c) 250 Mbit/s.

up to 250 Mbit/s. Corresponding eye diagrams taken at 155 Mbit/s and 250 Mbit/s are also shown in Fig. 6(b) and (c), respectively.

4. Conclusion

In summary, we have made what we believe to be the first demonstration of programmable color-tunable inorganic microdisplay, based on new epitaxial structures, μLED fabrication, and relevant CMOS technology. The microdisplay system reported here is capable of delivering computer-controlled programmable dynamic images with its emitting color changing from red to green at comparable brightness. Also, individual μLED pixels from this CMOS-controlled system have high-bandwidth modulation capacity, so that they can be used for high-speed VLC as well. To prove this, error-free data transmission at bit rates of up to 250 Mbit/s has also been demonstrated from a single representative pixel. Our future work in this area will focus on, first, optimizing or redesigning the wafer structure to increase the color-tuning range and the internal quantum efficiency of this material; second, investigating the modulation characteristics and relevant physical mechanisms of this high indium material; and third, roughening LED top surface or integrating a photonic crystal structure on the LEDs to help enhance their light extraction efficiency and power output at different colors. The work in this paper demonstrates a direct color-tunable GaN microdisplay for dual applications under CMOS control and, more importantly, provides an innovative method to overcome the limitations of using thin-film InGaN-based LED for multicolor applications in the future.

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