Full-Scale Self-Emissive Blue and Green Microdisplays Based on GaN Micro-LED Arrays

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ABSTRACT

Micro-size light emitting diode (µLED) arrays based on III-nitride semiconductors have emerged as a promising technology for a wide range of applications. If InGaN µLED arrays can be integrated on to Si complementary metal–oxide–semiconductor (CMOS) substrates for active driving, these devices could play crucial roles in ultra-portable products such as next generation pico-projectors, as well as in emerging fields such as biophotonics and optogenetics. Here we present a demonstration of, and methods for, creating a high-resolution solid-state self-emissive microdisplay based on InGaN/GaN semiconductors. An energy efficient active drive scheme is accomplished by integrating micro-emitter arrays with CMOS active matrix drivers that are flip-chip bonded together via indium metal bumps.

Keywords: Solid-state microdisplays, self-emissive displays, micro-LED array, III-nitride wide bandgap semiconductors, III-V and CMOS integration, active drive, flip-chip bonding

1. INTRODUCTION

In the last twenty years, high brightness LEDs based on III-nitride semiconductors have achieved dramatic advances alongside developments in indicators and solid-state lighting1. For example, InGaN-based white emitters have achieved a luminous efficacy of more than 150 lm/W, which is much higher than those of other self-emissive devices, such as organic LEDs (OLEDs) and electroluminescent emitters1. With the incorporation of multiple quantum wells (MQW) as the active region, LEDs have a narrow emission band of about 25 nm, providing a basis for high color purity and chromatic fidelity. With their intrinsic material properties and low voltage operation characteristics, LEDs have a much longer operational lifetime (> 100,000 hours), can be operated at extreme conditions such as high or low temperatures (-100º to 120º C) and humidity. All of these intrinsic properties make LEDs an ideal candidate for many applications where performance, reliability and lifetime are critical.

Since their inception3-7, µLED arrays based on III-nitride semiconductors have emerged as a promising technology for applications, including self-emissive microdisplays5-8, single-chip high voltage AC-LEDs for solid-state lighting9-11, and light sources for optogenetic neuromodulation12-15. The InGaN-based µLED array has opened a new avenue for the multi-site photostimulation of neuron cells and offers the opportunity to probe biological neuron networks at the network level13,14. In particular, III-nitride µLED arrays provide high brightness/contrast/resolution/reliability, long-life, compactness, operation under harsh conditions and are capable of high-chromatic fidelity.
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## SUBJECT TERMS

- Quantum Sensing
- Nanophotonic Devices
- InGaN/GaN
- Active Display
- Flip-Chip Bonding
- Indium Metal Bumps

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## SUPPLEMENTARY NOTES

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conditions and under bright daylight – properties which cannot be matched by more conventional liquid crystal display (LCD), OLED, and digital light processing (DLP) based microdisplay technologies\textsuperscript{16,17}.

Here, we present a successful example of III-nitride µLED array integration with Si CMOS to accomplish a high-resolution solid-state self-emissive microdisplay operating in an active driving scheme\textsuperscript{18}. The fabricated blue or green video graphics array (VGA) microdisplays (640 x 480 pixels) have a pixel size of 12 \( \mu \text{m} \), a pitch distance of 15 \( \mu \text{m} \) and are capable of delivering real time video graphics images. An energy efficient active driving scheme is accomplished by integrating micro-emitter arrays with CMOS active matrix drivers that are flip-chip bonded together via indium metal bumps. This success means that InGaN µLED arrays could play crucial roles in emerging fields such as biophotonics and optogenetics\textsuperscript{12-15}, as well as ultra-portable products such as next generation pico-projectors\textsuperscript{17}.

There have been a few reports on monolithic III-nitride µLED arrays\textsuperscript{5-8}. A monolithic µLED microdisplay is a microdisplay in which the µLEDs themselves and the interconnection between these µLEDs (the signal transmission paths, including all the metal lines for n- and p-type contacts) are all integrated on the same GaN wafer. This monolithic integration has the merits of easy and quick demonstration and characterization, since the microdisplay itself is an independent package, and the driving circuit can be designed using an off-the-shelf CMOS integrated circuit (IC) chip. However, to achieve a full-scale microdisplay in a monolithic µLED array, connecting the huge amount of control signals from a separate driving circuit to the microdisplay within a limited space is a very difficult if not impossible task. For example, a monochrome VGA format microdisplay with 640 x 480 pixels requires a minimum of 1120 connections to the rows and columns in order to drive the microdisplay. Given a pixel pitch of 15 \( \mu \text{m} \) (the perimeter of the microdisplay is only about 35 mm for VGA), wire bonding or tape bonding from the connections to the rows and columns in order to drive the microdisplay. Given a pixel pitch of 15 \( \mu \text{m} \), the number of signal lines will be increased by

\[ \text{number of signal lines} = \frac{35 \times 10^3 \, \mu \text{m}}{15 \, \mu \text{m}} = 2333 \times \frac{10^3}{12} = 1944 \times 10^3 \]

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In order to realize the full potentials of III-nitride µLED arrays, developing schemes to actively and energy efficiently drive the devices is essential, since it is envisioned that these devices will be operated on battery power and the efficiency of all components in the device package directly affect how long it can operate between charging. The challenge for achieving such a device is that III-nitride micro-emitters cannot currently be fabricated directly over Si IC circuitry. To overcome the above difficulty, we have employed the hybrid µLED microdisplay concept, similar to the widely deployed scheme of hybrid focal plane array detectors\textsuperscript{19}, which utilizes the technique of flip-chip bonding via indium metal bumps. However, the typical size of indium metal bumps used in hybrid focal plane array detectors is around 20 \( \mu \text{m} \).

The µLED layer structure used for microdisplay fabrication is shown in Fig. 1(a). Like conventional III-nitride LEDs, µLED structures were grown on (0001) sapphire substrates by metal-organic chemical vapor deposition (MOCVD). The insulating sapphire substrate provides an ideal platform as the display surface and for isolation between individual µLEDs. All of the emitter structures used are based on InGaN/GaN MQW confined between n-type and p-type GaN barriers. The emission wavelength was tuned by adjusting the In composition in InGaN alloys in the MQW active region. N- and p-GaN layers form the barriers and Ohmic contact layers. Effective hole injection is always an issue for III-nitride emitters due to

2. EXPERIMENT

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Proc. of SPIE Vol. 8268 82681X-2
the relatively large activation energy of Mg acceptors and low conductivity of p-GaN\(^{20}\). Reducing the contact resistance will enhance the hole injection efficiency, reduce threshold current and heat generation, and increase the device operating lifetime. For improved performance, we have adopted heavily Mg doped p-type GaN (p\(^{+}\)-GaN) layer as the contact layer to minimize the contact resistance\(^{21}\). The fabrication steps of III-nitride \(\mu\)LED arrays were built on previously reported procedures for etching and metallization\(^{22,3-11}\). CMOS active matrix 640 x 480 and 160 x 120 microdisplay controller ICs with \(\mu\)LED current of 0.5\(\mu\)A to 10\(\mu\)A have been designed and fabricated in a CMOS process.

Fig. 1 (a) Layer structure of \(\mu\)LED wafers. (b) Illustration of flip-chip bonding the \(\mu\)LED matrix array with the CMOS IC driver chip via the indium bumps to form a highly integrated one package microdisplay.

Figures 1(b) shows schematic illustrations of the microdisplay which consists of an array of InGaN micro-emitters as pixels arranged into matrix format on a sapphire substrate and the \(\mu\)LED array is heterogeneously integrated on to a Si CMOS IC driver chip using indium bump bonding. The polished back surface of the transparent sapphire substrate is used to display images. The pixels share a common anode (n-type contact) with independently controllable cathode (p-type contact). The hybrid integration of the InGaN microdisplay die with the Si CMOS driving circuit IC chip die means that hundreds or thousands of the signal connections between the microdisplay and the driving circuit have been accomplished in a single flip-chip bonding package through the indium metal bumps. This active matrix display also means that each pixel is geared with its own pixel driver circuit in CMOS that is capable of storing data and driving each individual \(\mu\)LED. The interface requirements of this hybridized package are thereby reduced to the few lines required for the signal and power connections.

### 3. RESULTS AND DISCUSSIONS

An expanded view under an optical microscope of a segment of an individually diced \(\mu\)LED array chip is show in Fig. 2(a), which illustrates more details of the fabricated devices. Micro-LED pixels and indium metal bumps fabricated by thermal evaporation on the \(\mu\)LED pixels seen from the transparent sapphire side are presented in Fig. 2(b). The results demonstrate ~ 6 \(\mu\)m indium bumps with excellent size uniformity.

Figure 3(a) shows a fully assembled InGaN microdisplay. Figure 3(b) shows a grayscale projected image of a leopard from a green InGaN VGA microdisplay (having 640 x 480 pixels) and reveals that the fabricated microdisplays are capable of delivering real time video graphics images. Figure 4 shows the measured characteristics of InGaN \(\mu\)LED pixels for blue and green microdisplays. The room temperature optical power shown in Fig. 4 was measured by a calibrated optical power meter placed on the sapphire side of a \(\mu\)LED array when a single pixel was lit. The nearly linear optical power output with increasing forward
current will be very useful for a range of applications, and ensures a high brightness microdisplay with a high dynamic range gray scale.

Fig. 2 Optical microscopy images of a full scale (640 x 480 pixels) InGaN µLED array. (a) The zoom-in image of a segment of a full scale InGaN µLED array chip. (b) The zoom-in image of a flip-chip bonded package with µLED pixels and indium bumps viewed from the transparent sapphire side.

Fig. 3 Demonstration of an III-nitride self-emissive microdisplay. (a) A fully assembled InGaN microdisplay operating at a driving current of about 1 μA per pixel. (b) A grayscale projected image of a leopard from a green VGA InGaN microdisplay (having 640 x 480 pixel with a pixel size of 12 μm and a pitch distance of 15 μm) operating at a driving current of 1 μA per pixel.

To obtain a sense of the microdisplay brightness, we characterized the luminance of the green µLED pixels. As shown in Fig. 5(a), a 12 μm pixel outputs roughly 1 mcd/μA and the luminance increases almost linearly with driving current (I) for I < 100 μA. For a microdisplay with a pitch distance of 15 μm, when
every pixel within the array is lit up and operates at 1 μA, the brightness of the microdisplay can be calculated to be ~ 4x10^6 cd/m^2. This luminance level is several orders of magnitude higher than those of LCD and OLEDs. Based on the pixel characteristics in Fig. 4, at I = 1 μA, a green µLED pixel has a voltage of around 2.6 V. This means that the power dissipation within the µLED array is only about 0.8 W for a full VGA (640 x 480 pixels) microdisplay if every pixel within the µLED array is lit up simultaneously. This estimate represents the upper limit of power dissipation since normally only a fraction (~25%) of pixels are lit up for graphical video image displays. Notice also that 1 μA driving current translates to a current density of about 0.7 A/cm^2 for a 12 μm pixel, which is about 1/30 of the typical value (22 A/cm^2) in conventional indicator LEDs, which have an average chip size of 300 μm x 300 μm and an expected operating lifetime exceeding 100,000 hours under normal operating conditions (i.e., I = 20 mA). These estimates also imply that the lifetime of III-nitride µLED array should be as long as those of indicator LEDs.

Fig. 4 Optoelectronic characteristics of µLED pixels. (a) I-V and L-I characteristics of blue µLED pixels. (b) I-V and L-I characteristics of green µLED pixels.

Another outstanding feature of InGaN based self-emissive microdisplays is their ability to operate under harsh conditions and at high or low temperatures. The operating temperature (T) dependence of the optical output power of our µLEDs has been measured and the results are depicted in Fig. 5(b). For the temperature dependence and radiance characterization, passive µLED array chips with 16 x 16 pixels (with 12 μm pixel size and 15 μm pitch distance) were fabricated. The luminance of µLED was measured by using a bare green µLED array chip (16 x 16 pixels simultaneously on) in conjunction with a 10-inch integrating optical sphere, and the single pixel radiance shown in Fig. 5(a) was obtained by dividing the measured value by the number of pixels (16 x 16 = 256). The temperature dependence of the relative optical power shown in Fig. 5(b) was measured by placing the optical power meter outside the optical window of a portable cryostat.
while the µLED array chip (16 x 16 pixels simultaneously on) was held inside the cryostat under a driving current of 0.1 mA. The intensity of the µLED emission decreased by about 10% when \( T \) was raised from room temperature to +100 °C and remained almost constant when \( T \) was cooled down from room temperature to -100 °C, while the operating voltage at 0.1 mA varied from 4.1 V at -100 °C to 2.9 V at +100 °C. This continuous reduction in the operating voltage with increasing \( T \) is due to thermal activation of free holes (\( p \)) described by the process of \( p \sim \exp(-E_A/kT) \), where the Mg acceptor activation energy (\( E_A \)) in GaN is about 160 meV. The \( T \) dependence of the µLED emission intensity in Fig. 5(b) represents the lowest thermal quenching ever reported for any type of microdisplay. The outstanding thermal stability is a direct attribute of III-nitride semiconductors.

Fig. 5 Confirmation of exceptional brightness and high thermal stability of InGaN microdisplay. (a) Luminance of a green µLED pixel as a function of driving current. (b) The temperature dependence of the relative emission optical power of an InGaN µLED array.

4. SUMMARY

In summary, we have achieved prototype full scale (VGA) high-resolution (with 12 µm pixel size and 15 µm pitch) self-emissive blue/green microdisplays, which are capable of delivering video graphics images for high brightness pico-projector and head-up/wearable display applications. Key advances include: (1) low contact resistance of µLEDs with 12 µm pixel size; (2) design and fabrication of an active matrix microdisplay driver circuit implemented in a digital CMOS process; (3) successful hybrid integration of InGaN µLED array die with Si CMOS IC chip die using flip-chip bonding via. Unique features of III-nitride microdisplays over other technologies are summarized in Table 1. Compared with microdisplays based on LCD, OLED, and DLP, microdisplays fabricated from III-nitride µLED arrays can potentially provide superior performance. Unlike LCDs that normally require an external light source, III-nitride blue microdisplays are self-emissive and result in both space and power saving and allow viewing from any angle without color shift and degradation in contrast. On the other hand, OLEDs must be driven at current densities many orders of magnitude lower than semiconductor LEDs to obtain devices with a reasonable lifetime and hence are not suitable for high-intensity use. DLP and laser beam steering (LBS) devices require the use of rapidly scanning microelectromechanical (MEMS) mirrors and separate light sources such as LEDs or laser diodes (LDs), which adds complexity, volume, and cost to the devices. Furthermore, the service lifetimes of MEMS and LDs are shorter than LEDs. Another distinctive feature of III-nitride microdisplay is its operating speed. Based on time-resolved electro-luminescence measurement, III-nitride
µLEDs have a very fast response. The measured turn-on time is on the order of tens of picoseconds. The operating speed of a µLED is limited by its turn-off time, which is on the order of 0.2 ns. This property ensures that the nitride µLED based microdisplays have a much faster response than LCD and OLED based microdisplays and opens up their potential uses as light sources for site selective fluorescence lifetime studies.

**Table 1** Comparison among various technologies for microdisplays.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Liquid Crystal</th>
<th>Organic LED</th>
<th>III-nitride µLED</th>
<th>Digital light processing</th>
<th>Laser beam steering</th>
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<tr>
<td>Mechanism</td>
<td>Backlighting/LED</td>
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<td>Self-emissive</td>
<td>Backlighting/LED</td>
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<tr>
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<td>1500 cd/m²</td>
<td>~ 10³ cd/m²</td>
<td>~ 10³ cd/m²</td>
<td>~ 1000 cd/m²</td>
</tr>
<tr>
<td>(green)</td>
<td>~ 10⁴ cd/m²</td>
<td>~ 10³ cd/m²</td>
<td>(full color)</td>
<td>(full color)</td>
<td>(full color)</td>
</tr>
<tr>
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<td>Very high</td>
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<td>&gt; 10,000:1</td>
<td>&gt; 10,000:1</td>
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<tr>
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<td>µs</td>
<td>ns</td>
<td>ms</td>
<td>ms</td>
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<tr>
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<td>High</td>
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<td>Short [limited by laser diodes]</td>
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