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# Exploring 3D Pixel Circuits for Small Pitch and High Brightness GaN Microdisplays.

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**Abstract**—Gallium nitride (GaN) based LEDs are a promising technology for microdisplays thanks to the brightness they can provide. However, they have not been widely adopted for this type of applications yet, partly due to the size and complexity of the associated driver circuits. In this paper, we demonstrate that despite the complexity of the driver circuits, a very small pixel pitch can be achieved thanks to CMOS 3D technology.

**Index Terms**—microdisplay, LED, 3D circuit, multi voltage, augmented reality.

## I. INTRODUCTION

Microdisplays are small dimensions display systems. Being of a small size, this kind of display is generally not intended for direct vision by the user, but is rather used in combination with an optical system magnifying the produced image. Due to their reduced size, microdisplays are a key component for head mounted displays such as augmented reality headsets [1], [2].

Like most of digital displays, microdisplays contain a pixel matrix, each pixel being individually controlled in order to generate an image. Two types of displays are particularly common, the lights processing ones, and the self-emitting ones. The light processing displays operate with an external light source, and depending on their pixels state, the light is stopped or allowed to pass through. Liquid crystals displays, and MEMS based displays belong to the light processing displays family. Light processing displays are out of the scope of this paper and will not be considered in the reported study, because of their limitations for the targeted applications. On the other hand, self-emitting displays' pixels are independent light sources, which are often LEDs on modern devices. To display an image, each pixel needs to be controlled in accordance to the input video signal. As display resolution increases, it becomes difficult to provide data through a dedicated link for each LED. Consequently, virtually all microdisplays use an active matrix. At any time, only one row of the matrix is selected and data provided to the columns only affect the selected row. Instead of leaving the unselected pixel off, each LED is connected to a driving circuit located underneath it. This circuit memorizes data when selected, and uses it to drive the LED when unselected.

Organic LEDs (OLED) have been used as light sources in self-emitting displays for more than a decade, and are still the most commonly used type of LEDs for this role [3]–[5]. OLED can provide a wide color gamut [6], offering the displays a good color rendering capability. OLED microdisplays can

reach very small pixel pitch thanks to their simple and compact pixel driving circuits. On the other hand, organic LEDs are known to suffer an important degradation during operation, especially when used under high current [7]–[9]. Although many mechanisms have been proposed to compensate for this degradation, they add complexity to the circuit. Furthermore, compensations are often done by providing more current to the damaged LEDs, accelerating their degradation. Consequently, despite the reported relatively high levels of brightness, OLED technology does not seem to be well suited for high brightness demanding applications (for example augmented reality devices can require a  $10^4 - 10^5$  cd/m<sup>2</sup> capable display to properly operate outdoor during a sunny day).

GaN based LEDs have been used in lighting applications for many years, and several microdisplays using these LEDs have been reported [10]–[13]. This LED technology suffers from a low maturity of manufacturing techniques at  $\mu\text{m}$  scale. Consequently, available micro-LEDs have more dispersed electrical characteristics and lower external quantum efficiency (EQE) than larger devices [14]. Because of GaN LEDs drawbacks, the simplest pixel driving schemes as sometimes found on OLED displays [15] don't seem suitable for GaN microLEDs which will require a more complex driving mechanism, thus limiting the ability to reach small pixel pitch. Thanks to its high brightness range (several order of magnitude higher than OLED), and the longer lifetime, GaN LED technology still gets lot of interest.

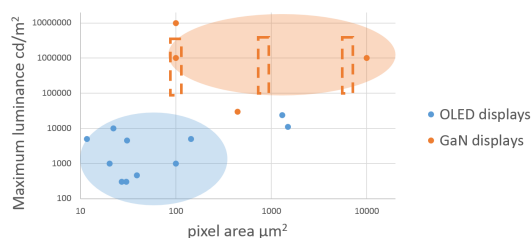


Fig. 1. OLED AND GaN displays performances.

The Figure 1 presents the brightness and pixels (or sub pixels for multicolor displays) area of displays reported the last few years. Dashed line rectangles represent displays for which only the pixel area is published and for which the brightness has been estimated based on the LED technology. This graph highlights the two different types of performances typically achieved with OLED and GaN, as well as the weaknesses of

these technologies (namely the limited brightness for OLED, and the relatively large minimum pixel area for GaN). In this paper we present a study on the possible reduction of GaN pixel pitch, using a 3D CMOS technology to implement the pixel driving circuitry.

## II. GAN DISPLAYS

### A. GaN LED

GaN based LEDs were reported to withstand high current density, and provide brightness as high as  $10^6$  cd/m<sup>2</sup> and  $10^7$  cd/m<sup>2</sup> [12]. It has been demonstrated that with the deposition of a GaN stack on the driving backplane, followed by the patterning of individual LEDs, pixel pitch as low as  $3\mu\text{m}$  is achievable [16]. Although to the best of our knowledge, no GaN oriented pixel driver with a matching pitch has been proposed.

The size of GaN LEDs has an influence on their characteristics, a given forward voltage results in higher current density through smaller LEDs. Under low current density, brightness-current density characteristic can be quite dispersed [17], and EQE is much lower for smaller LEDs. However the EQE gets similar for LEDs of all sizes, or slightly better for smaller ones under high current density [14], [18]. Consequently, in order to exploit GaN micro-LEDs at the best of their possibilities, they should be driven with a high current density. It shall be noticed, however, that GaN micro-LEDs current-voltage characteristic can be quite dispersed, one batch of 950 micro-LEDs has shown a current ranging over about two orders of magnitude for a forward voltage of 5V.

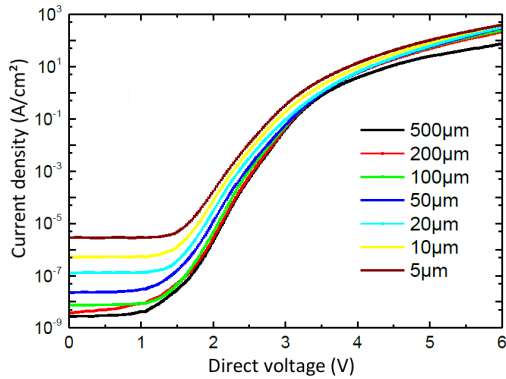


Fig. 2. Blue GaN LEDs current density versus applied voltage.

Figure 2 and Figure 3 are extracted from a previous work carried out in our institute [17]. They present the characteristics of GaN LEDs of different sizes. These characteristics are used in the reported study to determine the voltage and current to be provided by the proposed driving circuit, and the expected brightness.

### B. Driving scheme

Pixel driving circuits can power up a LED either by applying it a controlled voltage, or a controlled current. The current-voltage characteristic of the LED will determine the resulting

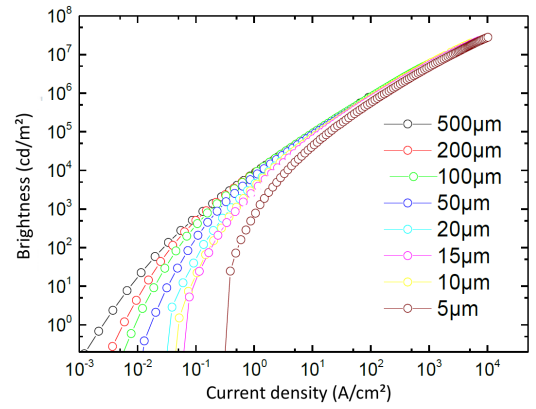


Fig. 3. Blue GaN LEDs brightness versus current density.

current through the LED in the first case, and the voltage on its terminals in the second case. The first solution known as voltage driving is commonly used in OLED displays, but would not allow a reliable control of a GaN micro-LED's brightness because of the characteristic dispersion mentioned above. Consequently the second solution known as current driving is the preferred one.

Good image quality requires both brightness uniformity across the pixel array, and a high enough color depth for each pixel (8 to 10 bits). As mentioned earlier, GaN micro-LEDs are not well suited for operation at low current density as EQE and LED to LED uniformity are quite poor under these conditions. In addition to the power efficiency reduction, the reduction of EQE at low current makes the brightness-current density a non-linear function even without taking dispersion into account. As a result, achieving different brightness levels for a pixel by generating different currents through the LED would not be a realistic solution.

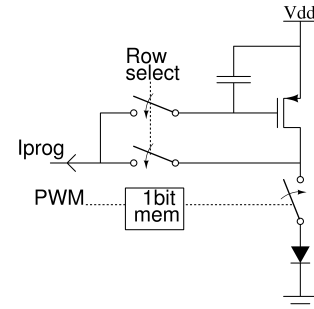


Fig. 4. PWM pixel circuit architecture.

Given the GaN microLEDs' specificities, a PWM driving scheme with a current source seems a good compromise between size and performances. Figure 4 illustrates the operation of this type of pixel. During the programming phase, the two programming switches (controlled by the Row select signal) are closed, and the current  $I_{\text{prog}}$  flows through the transistor connected as a diode. The gate source voltage corresponding to this current appears at the capacitor terminals. The programming switches are then blocked, and thanks to the capacitor

maintaining the transistor gate source voltage, the transistor acts as a current source generating a current equal to  $I_{prog}$ . This current is constant and sets the maximum achievable brightness, the grey level to be displayed is obtained modifying the LED ON state duration with the PWM signal. With PWM driving, the LED is always used with high current density regardless of the brightness to be displayed, and the achieved brightness depends linearly on the control parameter (LED ON state time in this case). However, PWM driving presents one major drawback with its extra complexity compared to other architectures, making it a generally less compact, and thus less conducive to small pixel pitch.

### C. Circuit achievable pitch

For a micro-LED with  $5\mu\text{m}$  pitch or less, a direct voltage of at least 4 V is needed to reach significant EQE and brightness [14], [17]. To reach the brightness of  $10^6\text{ cd/m}^2$ , which is one of the main reasons the GaN LEDs appeal for display applications, a voltage of 5V or more is needed. Consequently, the pixel driving circuit needs to sustain this voltage, and 5V compliant MOS are required. Minimum W/L for 5V MOS vary between technologies but is typically about  $0.5\mu\text{m}/0.5\mu\text{m}$ . Using these transistors to build a PWM pixel circuit as shown in Figure 4 would not allow to obtain a small pitch, as all the required transistors at minimal dimensions laying side by side would already take up about  $56\mu\text{m}^2$ .

## III. STUDIED SOLUTION

### A. Multi voltage circuit

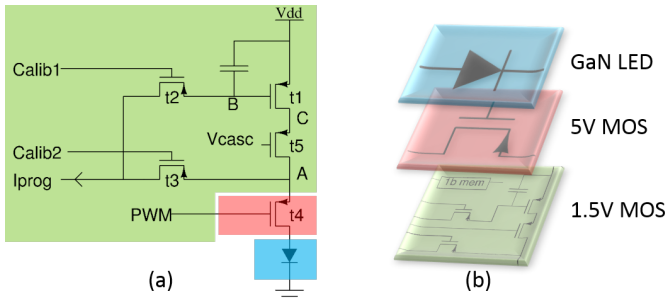


Fig. 5. PWM pixel circuit (a), pixel 3D construction (b).

The pixel circuit has to sustain 5V, however not all the transistors of the circuit need to do so. Having a part of the circuit operating under a lower voltage allows to use smaller transistors, and reduce the overall surface of the pixel circuit. The pixel presented on Figure 5(a) can be operated with  $V_{DD}=5\text{v}$  while  $t1$ ,  $t2$ ,  $t3$ , and  $t5$  are 1.5V compliant transistors, as long as the external signals Calib1, Calib2, and PWM (generated by the 1bit memory) stay in the range 3.5v - 5V. When the LED is ON, if its anode voltage drops,  $t4$  will enter in saturation region and act as a cascode transistor. When the LED is OFF (and the pixel not in a programming phase),  $t2$ ,  $t3$ , and  $t4$  are blocked but  $t1$  and  $t5$  are not. So net A's voltage will reach  $V_{DD}$ . During the programming phase, the pixel is protected because the whole programming circuitry is

designed to operate between 3.5V and 5V. In these conditions the voltage on net A will be maintained above 3.5V at all times preventing  $t1$ ,  $t2$ ,  $t3$ ,  $t5$  from being damaged by the 5V  $V_{DD}$ . With only  $t4$  being 5V compliant, lying side by side all the transistors (in minimal dimensions) of the proposed pixel takes less than  $18\mu\text{m}^2$ .

### B. 3D implementation

1.5V and 5V compliant transistors belong to two different technological nodes. Even though some technologies offer both types of transistors, the cointegration generally implies an increased number of technological steps, to obtain different gate oxide thickness or doping concentrations for example. With the aforementioned multi voltage pixel circuit, the surface dedicated to the 5V transistor and to the other transistors is in the same order of magnitude. Given these considerations, using a 3D technology to build the pixel circuit appears to be an interesting solution to further reduce the achievable pixel pitch by building the 5V transistor on a dedicated MOS layer. With this 3D repartition shown on Figure 5(b), the transistors lying side by side in minimal dimensions would take less than  $7\mu\text{m}^2$  on each layer. This type of 3D technologies is known to be capable of providing less than  $1.5\mu\text{m}$  bounding pitch [19], which is dense enough to provide the two contacts per pixel required between 5V and 1.5V layers in the studied pixel.

### C. Achievable pitch

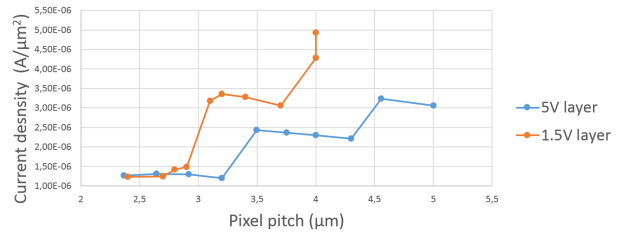


Fig. 6. Achievable current density versus pixel pitch assuming a square shaped LED.

The use of all transistors of the pixel in minimum dimensions gives an indication on the minimal pixel overall size, however the maximum current that this pixel can provide does not scale linearly with its surface. This is partly due to the control transistors, which take a significant part of the surface but do not scale with the rest of the pixel. Consequently for a given application requiring a certain brightness for the display, the minimum achievable pixel pitch with the proposed architecture can vary from the rough estimation obtained with all transistors in minimal dimensions. Figure 6 shows an estimation of the current density achievable by both layers of the proposed pixel circuit for different pitches. This estimation is made assuming the control circuitry operates under 1V (between  $V_{dd}$  and  $t4$ 's drain), leaving the rest of the power supply available for the LED. The plots exhibits staircases at pitches which, when reached, allow addition of a finger to some transistors. The decrease of achievable current density

	2k x 2k eMagin's display [20]	Leti GaN display [12]	Display using the proposed pixel (with 6v VDD)
LED technology	OLED	GaN	GaN
Circuit technology	180nm CMOS	130nm CMOS	3D:28nm SOI 1.5V(GO2) + 28nm bulk 5V(GO3)
resolution	2048 x 2048 x RGBB	873 x 500	2048 x 2048 x 4 / 873 x 500
Emitting surface	19.05 x 19.05 mm <sup>2</sup>	8.73 x 5 mm <sup>2</sup>	18.68 x 18.68 mm <sup>2</sup> / 3.98 x 2.28mm <sup>2</sup>
Pixel pitch	4.65 μm	10 μm	4.56 μm
Brightness	5 000 cd/m <sup>2</sup>	10 <sup>6</sup> cd/m <sup>2</sup>	≈5x10 <sup>5</sup> cd/m <sup>2</sup>

TABLE I  
COMPARISON BETWEEN EXISTING DISPLAYS AND PROPOSED ONE.

between these particular pitches is linked to a fill factor reduction (assuming the pixel maintains a square shape).

#### IV. DISCUSSION

The Table I presents a comparison of the performances of three microdisplays: an OLED one available on the market, a published GaN one, and an hypothetical one using the proposed pixel circuit. For this comparison, the hypothetical display is powered with 6V, so 5V remain available for the LEDs which can absorb a current density of 10<sup>2</sup> A/cm<sup>2</sup> (as can be provided by the driving circuit) to reach a brightness of approximately 5x10<sup>5</sup> cd/m<sup>2</sup>. The proposed display would match the resolution of the existing GaN one in a surface about four times smaller, offering a pixel density comparable with the OLED display. The proposed display can reach a brightness one order of magnitude higher than the OLED display. Although it doesn't match the brightness of other GaN LED microdisplays, the proposed device exhibits a pixel pitch only achieved with OLED technology, while maintaining a brightness typical of GaN based microdisplays. However it shall be noticed that some constraints like the management of heat dissipation, or voltage drop in the matrix power supply, were not taken into account to estimate the hypothetical display's performances, consequences of these elements are currently under study.

#### V. CONCLUSION

We have shown that at a pixel level, the use of 3D technology makes it possible to build a PWM driving circuit with a pitch as small as what is typically obtained with simpler driving schemes. This pitch reduction is obtained by folding the circuit on two superimposed active layers, and using two MOS technologies with different operating voltages. The proposed solution tackles the tradeoff between having high brightness and low pixel density with GaN LEDs, or a high pixel density but insufficient brightness with OLEDs, which leads the way for many outdoor portable display applications.

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