Challenges and Solutions for the Fabrication of CMOS-driven MicroLED Displays

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ABSTRACT

In this paper MicroLED and CMOS integration technologies are reviewed, from classical flip-chip to fully monolithic. These technologies address different challenges. MicroLED and CMOS integration technologies can be leveraged to fabricate microLED displays of all sizes and types, from AR/MR microdisplays to smartphone, TV displays and outdoor panels.

1 Introduction

GaN-based microLEDs has emerged as the key new display technology both for microdisplays and direct view displays. For microdisplays, GaN appears to be the only technology to provide ultrahigh brightness for augmented/mixed reality applications. For direct-view displays, microLED will allow better image quality, thanks to higher dynamic range and better colors, for applications ranging from smart-watch, smart-phone to TVs or outdoor panels. To make MicroLED microdisplays, it is necessary to couple arrays of light sources with the driving circuit (CMOS Active-matrix). In the case of direct view MicroLED displays, MicroLEDs are generally made separately and further transferred on a Thin-Film Transistor (TFT) backplane. However it has been also proposed to make microLED displays using CMOS driving circuit, as pioneered by Sony [1] and other big display manufacturers. In these cases, MicroLEDs and CMOS chip are placed separately in the pixel, and then connected, therefore do not require LED and CMOS integration.

In this paper we review technologies for hybridizing microLEDs with CMOS, and give latest results on hybrid bonding. Fig. 1 summarizes technical approaches already proposed to couple microLEDs with CMOS.

2 Overview of technologies

Today the dominating technology for emissive microdisplay is OLED. To fabricate such devices, OLED can be directly evaporated onto the CMOS active matrix, since the thermal budget for evaporation is low (less than 100°C) has no impact on CMOS devices. To fabricated GaN-based microdisplays the same approaches cannot be applied since GaN materials are grown are much higher temperature (more than 900°C). Considering this, the straightforward solution is to fabricate separately GaN-microLED array and CMOS, and couple -namely: hybridize - them afterwards. These last years companies and institutions have proposed several techniques to hybridize microLED array and CMOS, from flip-chip to high-resolution hybrid-bonding, as it can be seen on Figure 1, where we can also see alternative approaches such as monolithic technology.

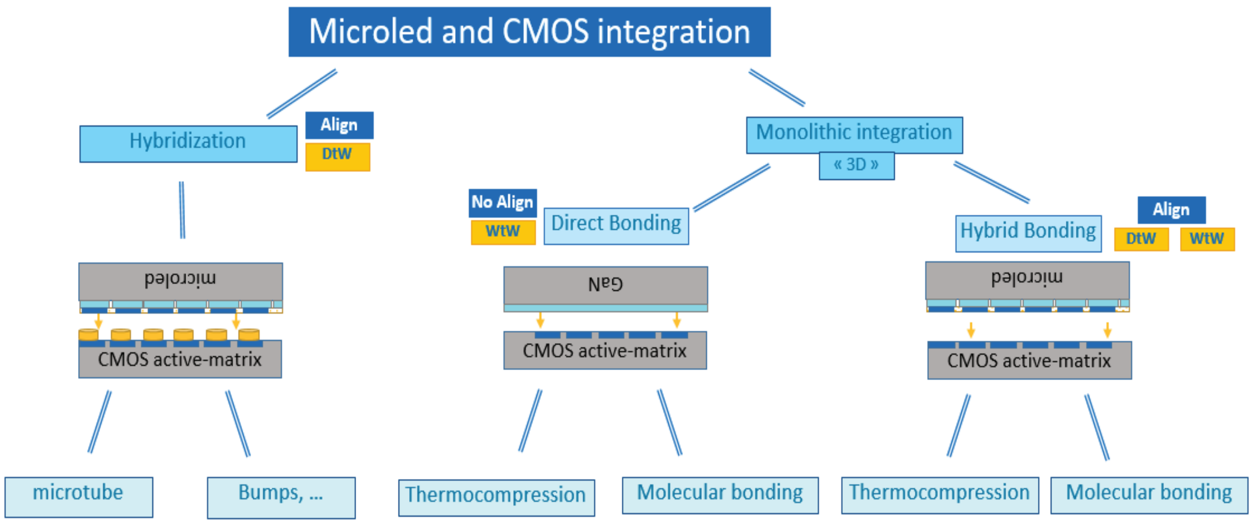

Fig. 1 Overview of MicroLED and CMOS integration technologies.

One can mention that some approaches need alignment of the two wafers, others do not. Note also possibility of Die-to-Wafer and/or Wafer-to-Wafer transfer. In the next sections we come into more details for each of these technologies.

3 Flip-chip hybridization

The first breakthrough in LED microdisplay was achieved by Texas Tech University in 2011, unveiling an active-matrix, high-resolution, GaN-based display capable of delivering video graphics images [2]. The device provided a 160 x 120 pixels resolution with a record pixel pitch of 15 µm. The integration between the LED array and Si CMOS driver IC was accomplished by flip-chip bonding using indium bumps. This technology, widely used in the semiconductor technology has limitation when reducing the pitch since it requires quite high thermal budget giving rise to differential dilatation of the two types of substrates, namely Sapphire and Silicon. To achieve smaller pixel pitch, new technology was needed. LETI has developed the so-called microtube technology which operates at room temperature. The principle of this technique is to grow microtubes on the pads of the silicon circuit (Fig. 2), deposit pads on each pixel of the GaN-array, align and couple both parts by simply applying pressure, the microtubes being then inserted in the GaN arrays pads.

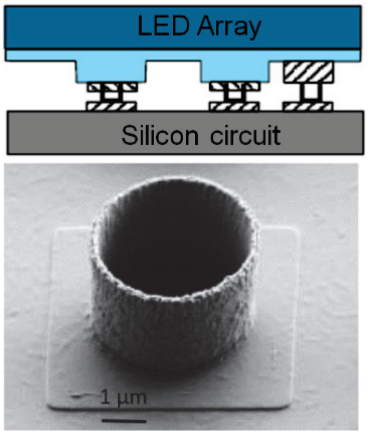

Fig. 2 (Top) Schematic of LED-array and Silicon circuit hybridization with microtube technology, (Bottom) Microtube grown on silicon circuit

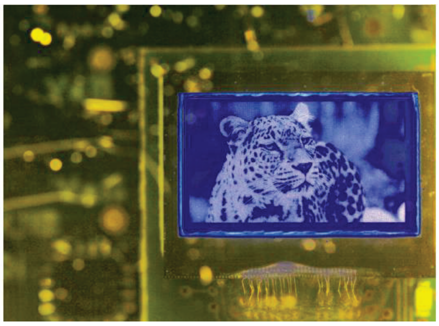

Fig. 3 WVGA, 10µm.-pitch, microLED prototype made with microtube technology [3].

With this technique pitch as small as 10 µm was achieved on a prototype with the highest pixel resolution (Fig 3).

Since then, to the author's knowledge no better result has been obtained using flip-chip hybridization. Microtube hybridization allows small pixel-pitch thanks to room temperature operation, and processs could probably be improved [4]. However, any type of connection (microtube, bump, pilar,..) has a limitation in feature size and, in addition, an alignment is needed. Therefore all flip chip hybridization will have a limit in pixel pitch and will not allow fabrication of LED microdisplays with pixel-pitch lower than ~5 µm.

4 Hybrid bonding

With Hybrid bonding, the metal architecture for connecting the two parts is strongly simplified since it is a simple metal pad, generally in Copper (Figure 1). This therefore unlocks the above mentioned limitation in feature size.

This kind of hybridization integration has been widely used these last years, mostly for the fabrication of image sensors, where connection pitch down to 1 µm have been obtained [5], but also for application such as High Power Computing or DRAM. More recently, it has been also applied for display application. Two types of bonding have been proposed: Thermocompression and direct bonding. Using thermocompression, in 2019 Sharp has demonstrated a full color display prototype with a pixel density of 1053 dpi [6].

Direct bonding allows pitches around 1µm that is why it is the best innovative solution for a direct interconnect for microled GaN based circuits and CMOS circuits both fabricated on different wafers and issued from different foundries.

In late 2021, LETI has demonstrated successful integration of 200mm-GaN/Si microled array with CMOS Circuit at a connection pitch of 3 µm [7].

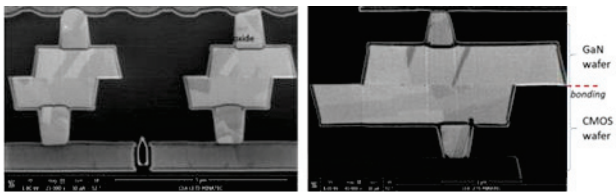

Fig. 4: FIB-SEM X-section of Copper /silicon oxide hybrid bonding area for 3 and 5 µm pitch

More recently, Micledi has announced targeting microdisplays made with wafer level 300 mm hybrid bonding with very small pixel pitch for AR/MR applications. They have achieved WtW bonding of 300mm GaN microled wafer with a Si-wafer with a few metallization layers [8].

In summary hybrid bonding strongly reduces the pixel pitch compared to more classical Die-to-wafer flip chip hybridization. There is a high interest in this technique by many companies and institutions, with very encouraging recent results. However with hybrid bonding an alignment between the microLED array and the CMOS wafer is always needed, and this will still limit the pixel-pitch reduction.

5 Monolithic integration

To achieve even smaller pixel pitches, it is necessary to get rid of the alignment. For this, a solution is to bond directly an epilayers on top of the CMOS, remove the epilayers substrate, and then pattern the pixels, which can be made very accurately thanks to the extreme precision of patterning in 200 and 300 mm semiconductor lines. In 2017 LETI has demonstrated that using this approach it was possible to make microled arrays with size of 2 µm and pixel pitch of 3 µm (Fig. 5). This was obtained by coupling a 200-mm GaN epi layer with a 200 mm Si driving circuit using direct bonding.

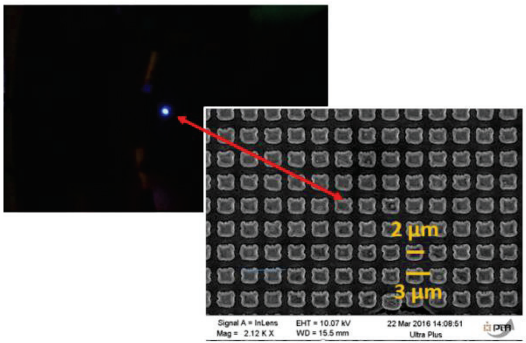

Fig. 5 (right) Scanning Electron Microscope image of a 2-µm size, 3-µm pitch blue microLED array and (left) one of the microLEDs switched on [9].

Jade Bird Display also uses this approach to couple GaN/sapphire epiwafers with CMOS drivers. In 2018, they showed that with coupling 100.-mm GaN/sapphire epilayers on 100.-mm CMOS wafer, they could obtain 20 µm-pitch microLED arrays with brightness over 1 Mnits [10]. Since then, they have drastically reduced the pixel pitch and built a complete product lineup of high-brightness microled microdisplays.

6 Integration of Led array and CMOS for large displays

The general approach for fabricating microLED displays is the following: First, Blue, Green and Red microLEDs are fabricated. Then they are singulated and transferred onto the TFT backplane, using mass-transfer. Among advantages, this approach leverages the existing TFT industry, TFT technologies, ….In the meantime, driving microLED devices appears to be more challenging for the pixel driving circuit (better device performance, more circuit complexity, ..), some challenges TFT may not fully answer. But CMOS certainly could. In 2019, LETI proposed a new concept for making microLED displays with CMOS circuit (Fig. 6). The key idea is to fabricate a series of elementary units and transfer them onto a receiving substrate containing only lines and columns. Each elementary unit consists of all-in-one- RBG MicroLEDs on CMOS driving circuit. Each unit is then transferred on one pixel of the receiving substrate.

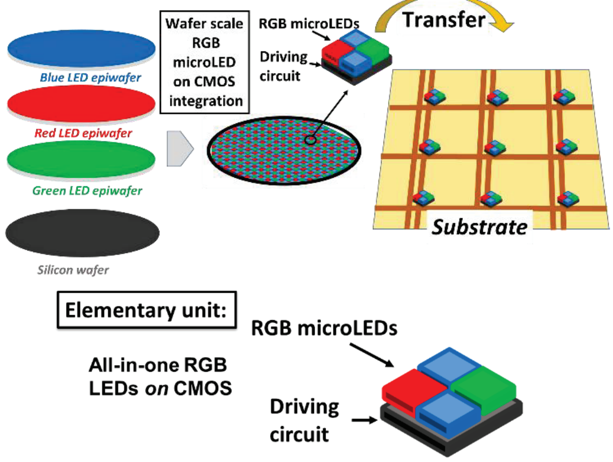

Fig. 6 (Top) New approach for fabricating microLED displays with CMOS driving and simpler transfer, (bottom) elementary unit consisting of all-in one RGB LEDs on CMOS driving circuit [11].

The first advantage of this approach is on the performance side: CMOS driving provides the best device performance, highest integration, and therefore it is the best solution for the extremely demanding conditions of the microLED driving. Another advantage is that it leaves free space in the pixel, which can then can embed other functions that purely light emission: image sensing, actuation, ... opening a wide field of new applications and markets.

This approach requires coupling microLED arrays with CMOS wafer. It could be potentially made with any kind of coupling technology we have reviewed here.

7 Conclusions

We have reviewed MicroLED and CMOS integration technologies, from classical flip-chip to fully monolithic. These technologies address different challenges, the connection pitch is one of them, since it rules the pixel pitch. A huge number of companies and institutions are involved in, and big progress is made. Overall, MicroLED and CMOS integration technologies can be leveraged to fabricate microLED displays of all sizes and types, from AR/MR microdisplays to smartphone, TV, to outdoor panels.

Aknowledgment

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