MicroLEDs: Where Are The Successes and What Are The Challenges?

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ABSTRACT

MicroLEDs have offered the promise of a light engine with high luminance, extraordinary efficiency, long lifetime, and high color purity. Despite a 25 year history, these performance advantages, and a substantial investment in both microLED development and manufacturing capacity, there are only a few commercial products that incorporate true microLED technology in commercial production. This presentation will discuss the benefits, challenges, and successes for microLEDs in both display and non-display applications.

1 Introduction

MicroLEDs were first demonstrated by Jiang and Lin in in 1999,[1] and have followed a steady cadence of technical progress, commercial development, and advances in processing and technology.[2] Despite this strong history and the potential for extraordinary figures of merit in nearly all figures of merit for displays (including luminance, primary color purity, efficiency, and lifetime), there are limitations to the technology which are being addressed by the community. The recent development of a range of new technologies to address these complications has led to a number of recent breakthroughs which are paving the way towards commercial implementation.

1.1 Taxonomy of microLEDs

One challenge in the discussion of microLEDs is the diversity of formats and applications that can be considered. Perhaps the best understood display format is the microLED microdisplay, as initially proposed in [], which can be used as a projector or as a light engine for use in an AR/VR/MR system. Since the luminance of microLEDs is so high (20-50M+ nits), these devices are typically used in an indirect view system in which the light is processed through optics before exposure to the viewer's eye.

A second approach is the fabrication of direct view displays using microLEDs. Of course, it is possible to use a microdisplay as a direct view device for small displays (as in [3]), but this approach is relatively expensive in the use of material relative to the potential of the material. The use of chiplets which reduce the LED area in use has been extensively explored (e.g. [4]) which can offer a substantial (100-1000x) improvements in the efficiency in material usage and further offer a number of integration advantages (including integration on opaque, transparent, or even flexible and stretchable formats).[4,5]

An additional consideration is how the semiconductors in microLEDs are deposited and grown. Many microLEDs start with epitaxially grown LED wafers using more or less conventional growth processes and device stacks to fabricate the light emitting elements.[6] The need, however, for multiple colors and higher levels of integration have also led to innovation in this area. In addition to bonded [7] and sequentially grown multi-color and multi-function wafers,[8] nanowire [9] and hybrid growth approaches have also enabled both the integration of multiple colors on a single substrate and the hybrid deposition of LEDs onto silicon wafers, eliminating the need for hybrid bonding or transfer steps.

2 Technical Successes

There are a number of technical challenges that have been addressed in the community to advance microLEDs to their current state of performance. A few of the most important areas of inquiry and advance are discussed next.

2.1 Assembly yield

One of the challenges for mass transfer technologies (which has particular relevance for direct view displays) has been the complexity and high barrier for high throughput and high yield of millions of pixels and subpixels. Even a modest display (e.g. XGA resolution) requires more than two million subpixels, and the yield challenges are substantial.[10] Modern display quality expectations demand near perfection, and even a single "stuck on" pixel, can lead to rejection of a Class I display.[11] A broad array of approaches have been proposed including selective laser transfer,[12] use of highly parallel elastomeric transfer media,[13] and fluidic assembly have all shown success.[14]

Yield enhancement approaches have also been important to boost overall yields following the transfer process. The use of intermediate transfer/check steps allows for the guaranteed transfer of known good LED chiplets.[15] The ability to effectively use redundancy,[16] inline / non-contact metrology,[17] and repair are promising approaches for enabling the effective implementation of high pixel count microLED panels through yield enhancement.

2.2 LED efficiency

LEDs can be extremely efficient. It was previously the case that green LEDs were less efficient and available than blue devices, but recent advances have closed this “green gap” and solutions such as down conversion of blue LEDs (which at one time offered a better efficiency than native green LEDs) are no longer necessary.[8]

Red LEDs do continue to offer some efficiency challenges, but there is promise there as well. In addition to the overall improvement of LED efficiency, of particular relevance to microLEDs is the development of red LEDs which are on the compatible material platforms (i.e. AlInGaP) as green and blue GaN LEDs, offering the potential for hybrid integration in a single wafer and unified processing approach. The use of nanowires as well as hybrid templating approaches offer continuing promise in this direction.[18]

2.3 Luminance

LEDs natively offer a high luminance at their surface. Depending on the color, it is realistically possible to achieve 20-50M nits at the LED element when driven at the peak current density (which can be as high as 100A/cm^2). This high luminance drives the potential for microLEDs both in the AR/VR space as well as the mass transfer direct view space, where a low fill factor can be used.

One of the challenges, however, for achieving high luminance is the interaction of luminance and efficiency. The highest efficiency is achieved at relatively low current density; this leads to some tension in the management of pixel size.[19] While small pixels are often considered to be favorable, the higher current density needed in a small pixel may lead to a lower system efficiency, and when not needed, should be carefully considered.

2.4 Color management

LEDs natively offer excellent color points, easily exceeding the DCI color gamut without the need for filtering or down conversion in native LED structures. One of the challenges, however, has been the need for the fabrication of a full color RGB using disparate material systems (especially GaN for blue and green, and InGaAs for red). In a mass transfer approach, it is relatively straightforward to select different LED compositions for each of the color elements.

Several approaches have been proposed in the fabrication of full color microdisplays, where it is more complicated (but not impossible) to mix different LED materials. Light engines can incorporate more than one panel, and combine the three wavelengths using external optics.[20] The use of quantum dots with filters has also been effective in the fabrication of full color microLED microdisplays.[21] Stacked multi-color LEDs have also been shown, both through hybrid bonding [22] and sequential templated growth [8] or the use of selectively deposited nanowires.[9] A range of new phosphors have also been developed which overcome some of the limitations of quantum dots as a color down conversion medium (especially optical density and self-absorption).[23]. These new phosphors can be considered both for microdisplays and mass transfer systems.

2.5 Drive management

It is essential to drive microLEDs using an active matrix for any reasonable resolution display. Even if a microLED display is driven at a low average luminance, an active matrix is required. An active matrix can overcome the high current drive that is otherwise required during the selection phase of a passive matrix display drive, which is a challenge for interconnects.

There are a few major approaches that have been seen in the integration of an active-matrix drive. One, which has been pursued by our group, is the use of a monolithic thin film transistor backplane co-integrated with the LED elements.[24] This approach has the advantage of a high yield and low cost per unit area for both mass transfer and microdisplay families, but has the limitations of the performance of thin film transistors in the structure.

A second approach has been the hybridization of the microLED wafer with a silicon integrated circuit offering device drive through the silicon and inheriting many of the advantages of the silicon backplane such as more advanced electronics and signal processing.

A third approach is the use of a thin film transistor backplane on a glass substrate for mass transfer microLEDs.[25] Backplanes similar to those that might otherwise be used for an AMOLED have been demonstrated, and are well aligned with the infrastructure available for display panel manufacturing.

A fourth approach that has been proposed is the use of microICs for the display drive.[16] This may be the best of all worlds, offering both a high efficiency in the drive electronics in terms of area utilization and cost, while also offering the performance of a silicon integrated circuit. A challenge with this approach, however, is the large silicon content, which can be expensive.

There are a number of other promising approaches that have also been demonstrated. Of particular interest is the depletion structures shown in [27], which allows for an active control without the need for an additional transistor backplane. This approach offers the potential for a high yield and low cost for the development of an active drive for the LEDs. Other groups have built “magic wafers” which include both high performance transistors together with the LED to incorporate the control in a single unified structure. (e.g. [10])

3 Challenges

While there have been a number of advances in assembly yeid and in-line test as well as color management and conversion, there remain a few challenges of great interest to the community.

3.1 System efficiency

While LED efficiency has been addressed through improvements of the materials used, system efficiency is a combination of the circuit design, pixel layout, and choices made in the drive sequence. There remains substantial development in this are to further advance microLED efficiency overall.

3.2 Thermal management

LEDs can be relatively efficient when compared with other emissive technologies, but even a 50% or higher wallplug efficiency means that there is substantial waste heat that needs to be extracted from the LED elements. At full intensity, LEDs can consume more than 300 W/cm^2 , and one can consider at least half of this will be rejected as heat in a practical system (this is before we consider any efficiency loss due to the control electronics). For comparison, a heated element on a stove is 3-5 W/cm^2. Especially for microdisplays, but also for mas transfer displays, this requires some advanced attention – LEDs drop substantially in efficiency as their temperature exceeds 100C, and advances in substrate engineering, heatsinking, drive management for high efficiency are all needed to overcome the heat and temperature limitations that might otherwise be seen in LEDs.

3.3 Pixel size

There have been a number of demonstrations of extraordinarily small pixel sizes demonstrated, and small pixels (especially at high efficiency) are absolutely desirable for microplay applications, where a large number of pixels need to be formatted into a small area. Depending, however, on how the pixels are formed there are some potential complications and tradeoffs in the aggressive miniaturization of pixels. Smaller pixels for an equivalent overall display luminance means a higher current density, which can unnecessarily lead to a lower efficiency in the display.

4 Market successes

There have been a number of commercial product announcements in the microLED area – while a comprehensive list would be nearly impossible to compile at this stage (and with apologies for the many omissions any such list will necessarily have), a few commercially released products can be noted along with the benefits microLEDs grant at the system level. Three that can be immediately highlighted include:

Sony Crystal LED is a direct view chiplet based technology:[26] Sony, which launched the commercial microLED world with its announcement of the Crystal LED display at CES in 2012, has advanced its microLED tiled large format displays under the Crystal LED brand. These systems are now extensively used for direct presentation displays, virtual production,

Jade Bird’s line of indirect view microdisplays: These light engines are used in a number of AR/VR microdisplay systems, including the TCL RayNeo X2 and X3 Pro. These demonstrations show the potential for these light engines to supply the luminance needed for low efficiency optics in a high backlight environment.

AUO’s direct view wearable display: Use of a circular display in the Garmin fēnix 8 Pro MicroLED smartwatch. This system shows the potential for a daylight readable always on high efficiency system built using microLED.

5 Conclusions

While many of the challenges in developing microLED displays have been addressed by a range of research organizations, there is still substantial work to be done to further commercialize the technology. The development and adaptation of microLEDs for high value display and non-display applications will continue to require additional innovations both in technology as well as the adaptation of both existing (and potentially new!) packaging, integration, drive, processing, material, and circuit innovations to address the diverse needs of customers and the community.

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