

A Brief Survey of MicroLED Technologies

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Abstract

Micro-LED displays, in which LEDs are controlled at the individual pixel level to form high-resolution information displays, offer the opportunity to develop systems with extraordinary properties. In this work, we will offer a brief survey of the field, including a taxonomy of microLED displays, limits to scaling, and a discussion of the major modern approaches for fabrication, assembly, and drive.

Author Keywords

microLED; microdisplays, mass transfer

1. Introduction

Inorganic light emitting diodes offer unparalleled efficiency, lifetime, luminance, and spectral quality in a controllable light source. Because of these exemplary characteristics the fabrication and placement of LEDs as single pixel elements and the control of those LEDs, a concept generally known as microLED, has developed as an area of active investigation and development. This work will briefly survey the microLED field and discuss several of the challenges currently being addressed in the area.

2. Taxonomy of microLED displays

LEDs offer extraordinary characteristics, unparalleled by other artificial light sources. In particular, LEDs offer an exceptional wallplug efficiency (exceeding 80% for blue), extraordinary luminance (10-50M nits), extraordinary lifetime (greater than 100 khrs), and the potential for the development of color primaries with a gamut second only to the use of lasers (and, in practice, nearly imperceptibly worse than laser light).

There are two major approaches to the fabrication of microLED displays. Direct view systems, which typically have a target luminance of less than 20,000 nits (and more typically target 1000-2000 nits) only require a small fill factor of 20-50M nit LED materials, and are typically fabricated through the distribution of small chiplets over a large area. Other applications, such as projectors and augmented/mixed reality, can benefit from a high intensity microdisplay and convert the illumination to a useful format using interstitial optics. This distinction can separate the approaches used and target applications into two major areas; mass-transfer displays for direct view, and microdisplays for indirect view applications.

Separately, there are also several approaches to the development of the LED material itself. While many microLED displays use LEDs fabricated using traditional epitaxial approaches (e.g. MOCVD on sapphire), there is also significant advantage to alternative LED fabrication methods such as the use of nanowires, especially for the development of full color devices.

The approaches used to create full color systems offers another area of differentiation for new approaches.

3. Addressing and the need for active matrix technologies

LEDs have a non-linear, rectifying character and can be driven in scaled passive matrix configurations. Despite this nominal potential use, there are significant scaling challenges associated with driving LEDs at their full intensity in a passive matrix approach. LEDs can be driven at peak current densities exceeding 20A/cm², which leads to a significant total current when displays are driven at full intensity.

During a passive matrix drive, there are three scaling effects on the total current – the number of pixels switching current into the line, the number of resistors in series, and the overdrive for each frame all contribute to the voltage drop across the row. It can be shown that the total voltage drop is given by:

$$\Delta V_{max} \approx \frac{n}{2} I_{px}^{dc} R_{cell}$$

Where I_{px}^{dc} is the average current density over the frame and n is the number of rows. While the exact expression includes both the number of rows and columns, the two are in proportion while scaling the display.

While an analysis of the scaling is beyond the scope of this paper, even with a very minimal series resistance, the required drive voltage quickly escalates once we consider displays of any practical resolution at reasonable luminance. This consideration applies to both large panels and microdisplays. The solution to this problem is to change to an active matrix configuration; since an active matrix can drive a pixel during the entire addressing period, an active matrix does not require an overdrive. This leads to significantly less loss, and a peak voltage drop of:

$$\Delta V_{max} \approx \frac{n^2}{2} I_{px}^{dc} R_{cell}$$

Which is a significantly more attainable scaling characteristic for high resolution and high information content displays. It is for this reason that much of the work for microLED displays is focused on approaches that assemble the LED elements together with transistor backplanes.

LED efficiency: One of the challenges for LEDs is the efficiency depends strongly on the drive current; there is a current at which the LEDs achieve a peak efficiency, and current densities lower and higher than this peak offer a lower quantum yield. [1] (Fig 1) In addition to considerations of maximum efficiency, these efficiency droop effects pose a challenge for predictably driving LEDs at a programmed luminance. Because of this significant variability in efficiency, many microLED displays are driven in a PWM mode both to yield predictable output luminance and to drive the LEDs closer to their maximum efficiency. Chiplets, as they are made smaller, also

increase in sidewall area which can decrease the overall efficiency.

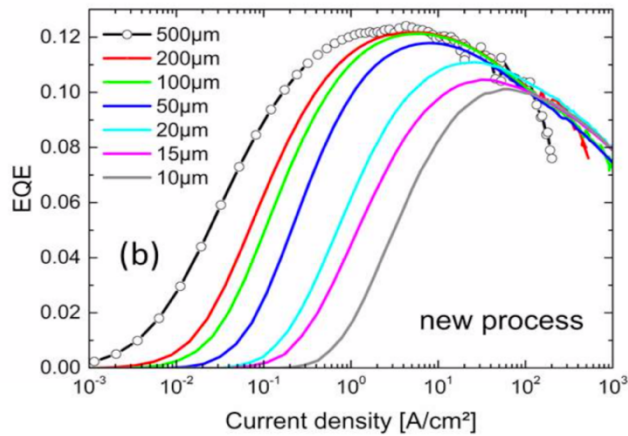


Figure 1. Efficiency curves from [1] for microLEDs of different sizes.

Thermal considerations: In addition to a change in efficiency with current density, the efficiency of LEDs also changes with increasing temperature. While the efficiency of LEDs can be very high, there is still significant loss internal to the LED, which leads to heating effects and a need for effective heatsinking in such displays.

Color conversion: Many of the approaches proposed are capable of using heterogeneous LEDs for building displays; in those cases materials with a varying bandgap can be used. It is favorable, however, in many circumstances to build a monochrome display and convert the color. This allows for both higher efficiency in many circumstances (e.g. for the formation of green pixels, for which direct LEDs are not nearly as efficient) and the use of a single substrate (e.g. at 405 or 470nm) to drive a full color display. There are a number of techniques that have been proposed to achieve this color conversion and develop full color displays including the use of quantum dots, phosphors, and nonlinear wavelength conversion structures.

4. Direct view / large panel displays

One of the best-known uses of LEDs is the application to video walls, which are used in many 100" and larger indoor and outdoor display installations. Packaged LEDs can be used for large format direct view panels with pixel pitches greater than 1mm, and new "mini-LED" formats with pixel pitches well below 1mm are now available using packaged components assembled on circuit boards and glass interposers. Advances in image correction, the format of hybrid assembly, and the relatively large inter-pixel format for video walls allows for tiles to be seamlessly arranged in increasingly aggressive scaled devices, allowing for both arbitrary size and interesting shapes (including curved and non-rectilinear panels) in display assemblies.

Looking towards scaling to well below 1mm pixel pitches, there is significant innovation in the singulation, placement, connection, substrate formatting, and addressing of LED chiplets using what are generally known as mass transfer approaches. Significant innovation has been applied to the use of

techniques that allow for large numbers of unpackaged LEDs to be placed and connected, including the use of highly parallel pick and place strategies, patterned laser transfer, and fluidic self-assembly.

In addition to the potential for developing extraordinary displays, an additional exciting dimension of this approach is that the LEDs occupy only a small fraction of the substrate area. A directly viewed display with a peak luminance of 1,000 nits needs less than a 1% fill factor of 10-50M nit LED material.

This opens significant opportunities for the use of optically and mechanically interesting substrates where the substrate properties dominate the characteristics of the device. Mass-transferred microLEDs can be used to build flexible, stretchable, transparent, and black displays unlocking a range of new application areas and formats.

Many challenges face these mass-transferred LEDs, including the requirement for rapid placement of a large number of parts, binning and sorting of the LED materials, and high demands for yield. Many of these challenges offer significant additional opportunities for innovation.

5. Indirect view microdisplays

The extraordinary luminance and efficiency of LED displays also lends microLEDs to the development of indirect view microdisplay applications. Such devices offer broad potential applications in projection, augmented/mixed reality displays, and non-display light engine applications (e.g. for lithography or 3D printing).

There are a number of interesting approaches that have been proposed and demonstrated for microLED integration with drive circuitry to allow for active matrix addressing. Much of the early and current work focuses on the hybrid assembly of patterned LED structures onto integrated circuits that provide the LED drive; several pioneering microLED microdisplays are of this type.[2,3] (Fig 2, 3) More recent work has also shown the transfer of layers of active LED material directly onto silicon, as well as the development of thin film transistor backplanes directly on the LED for device integration.



Figure 2. The bonding approach pioneered in [2] for incorporating an active matrix with an array of structured microLEDs. Reproduced with permission by the American Institute of Physics. This structure shows the fine pitch achievable using hybrid bonding techniques.

6. Nanowire and multicolor wafers

One of the challenges in the microLED field is the availability of LED material in multiple colors. While traditional MBE and MOCVD epitaxy deposits material across the entire substrate, there has been significant recent work in the development of substrates capable of supporting multiple colors in an area selective format.

Selective area epitaxy (SAE) allows for masking limited areas and permitting the growth of semiconductor stacks in different parts of the wafer. SAE has been used to create multiple color substrates, as well as hybrid LED substrates that also simultaneously support circuitry for pixel selection and drive.

Nanowire LEDs also offer a significant area of opportunity for the fabrication of hybrid substrates. Nanowire growth technologies allow for the deposition of high quality semiconductor material with a relaxed requirement for templating on the substrate. This permits the deposition of dramatically different semiconductors on a shared substrate arrangement. When coupled with SAE techniques, nanowires can be used to create multiple semiconductor elements, allowing for the deposition of multiple colors on a common substrate. Nanowires also offer the potential for enhanced light extraction and management of the light output cone through engineering of their optical properties. Nanowire-based substrate material offers the potential for significantly new display formats with multiple colors in a single wafer, as well as the potential integration of drive and emissive circuitry in a single device.

While LEDs have decreased significantly in price over the past 20 years, there is still significant room for additional price efficiency. One of the more exciting recent developments has been the demonstration of LED-grade GaN growth on silicon substrates. This opens the opportunity for significantly reduced LED cost (silicon substrates are less than 1/5 the price of sapphire, and perhaps 1/20th the cost of SiC substrates) while still delivering excellent thermal performance and improved post-process flexibility through machining and release from the silicon substrate.

7. Color conversion and formatting

The wavelength output for each LED is fixed by the composition of the epitaxy of the material. It is favorable in many circumstances to fabricate array devices in blue or UV wavelengths and to use color conversion techniques to develop full color displays; several approaches have been proposed and demonstrated for full color display technologies. The challenges and technology approaches for color conversion and light shaping will also be discussed in this work.

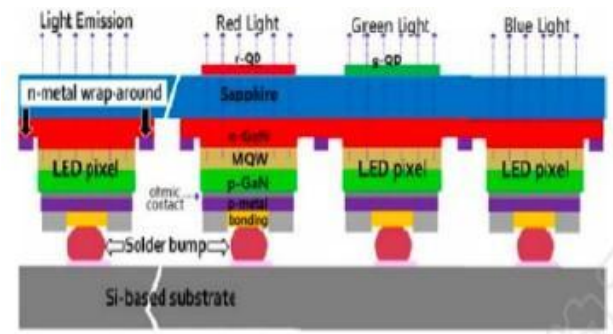


Figure 3. Color conversion approach presented by Wei, et al., in which quantum dots and filters are used to build full color LED devices [3]

Conclusions

MicroLEDs offer many potential advantages in both large area and microdisplay formats, and are poised to transform a range of next generation of display devices. Future work will include addressing many of the scaling, cost, and efficiency issues inherent in the technology. While the first areas of market penetration are not yet known, it is certain that the next few years will be an exciting time for further development and innovation in the technology.

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