Technical and Manufacturing Challenges in MicroLED Processes

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Abstract

Over the last decade, the focus of LED technology development has expanded from traditional emitter-level performance improvements to establishing a wide range of novel technologies with distinct applications. In particular, in recent years, the development of MicroLEDs has attracted significant interest due to their wide range of applications, from wearable displays to matrix automotive headlights. MicroLED technology is very enticing, however, it also presents extreme and wide-ranging technological and manufacturing challenges, from the epitaxy development all the way to the packaging process. In this paper, we will discuss the technical and manufacturing challenges of MicroLEDs, and also present state of the art red, green and blue MicroLED performance. Moreover, we will also discuss how device efficiency can benefit from the presented level of performance using various material systems, along with optimal driving conditions for different MicroLED sizes and applications.

INTRODUCTION

In recent years, the development of MicroLEDs has attracted significant interest and commercial investment for a wide range of applications due to their enticing nature of meeting the ultimate display requirements of high image quality, fast response, high luminance with low power consumption, small form factor, high reliability, and, in some cases, transparency. [1,2] One key example can be found in automotive applications, where matrix headlighting utilizes MicroLED arrays with pixel sizes on the order of tens of microns. This application requires medium to high brightness with an emphasis on lifetime and reliability, while meeting the stringent demands and regulations of the automotive industry. In addition, MicroLED arrays with pixel size less than 10 um, are envisioned for wearable display applications such as smart watches, with the promise of offering high dynamic range (HDR) and low power consumption. Another application ultimately benefiting from MicroLEDs due to their HDR and high efficiency is in miniaturized projection displays for augmented reality (AR) devices. Such AR applications require the highest pixel densities, with MicroLED sizes approaching 1um or less.

To realize these MicroLED technologies, III-V compound semiconductor materials systems such as AlInGaN (for blue, green, and red emission) or AlInGaP (red emission) have been chosen due to their best combination of high brightness, dynamic range, and robustness. However, even though the methods of manufacturing conventional mini and large size III-V semiconductor LEDs are well-known and mature, when it comes to microLEDs there are several additional technical challenges, and there is no agreement in the optimal method of their fabrication. In this paper, we will discuss the technical and manufacturing challenges of MicroLEDs, and also present state of the art red, green and blue MicroLED performance. Moreover, we will also discuss how device efficiency can benefit from the presented level of performance using various material systems, along with optimal driving conditions for different MicroLED sizes and applications.

RESULTS AND DISCUSSION

One of the main challenges for the development of MicroLEDs lies in the reduction of External Quantum Efficiency (EQE) for smaller MicroLED pixel sizes. This reduction in EQE can be attributed to the effects of both the Internal quantum efficiency (IQE) and the extraction efficiency (EXE). As device dimensions shrink, the surface-to-volume ratio of the emitter increases, and the role of defects at the semiconductor surface (which cause non-radiative recombination centers) becomes increasingly important with regard to affecting the IQE. It is therefore extremely critical to control and passivate the surfaces. Moreover, traditional methods of increasing the EXE that are employed in larger devices may become impractical for the needs of applications that require ultra-small pixel MicroLED emitters. We have previously reported the performance of Lumileds' epitaxy fabricated into MicroLED arrays with various mesa sizes as summarized in Fig.1. [3] In each array, all the mesas are of the same size and are connected in parallel to a continuous n-type semiconductor layer. An identical MicroLED die fabrication process was used for the arrays of the three InGaN colors presented. A different die fabrication process has to be used for the AlInGaP arrays, but differences that might distort efficiency comparisons to InGaN red have been minimized to the extent possible. For the InGaN arrays, we observe a decreasing sensitivity of the EQE to mesa size with increasing wavelength (with practically zero sensitivity for red). Similar observations have been reported by others and were speculated to be related to differences in the carrier lateral diffusion length within the QWs depending on the indium concentration. [4] AlInGaP red is capable of much higher efficiency than InGaN red for the mesa sizes down to around 4um, as long as the system has no hard upper constraint on current density. However, AlInGaP red needs to be driven at significantly higher current densities than InGaN blue and green due to the higher sensitivity of AlInGaP to surface recombination losses, which can result in additional complications at the system level. Various scenarios to optimize the display driving schemes will be discussed in detail during the conference presentation.

Regarding the manufacturing challenges in MicroLEDs, unlike traditional larger-size LED manufacturing, MicroLED array fabrication requires a system level integration from epitaxy to display on the CMOS backplane, which induces enormous complexity to the process. Each added process step can introduce new defects and methods to minimize defect introduction and to optimize the yields are some of the key challenges. Furthermore, the sizes of MicroLEDs are often too small to be evaluated by conventional metrology, therefore, new test methods have to be developed. Optimizing each process step can minimize the overall risk. In the presentation we will also discuss a latest case study in automotive headlight modules.

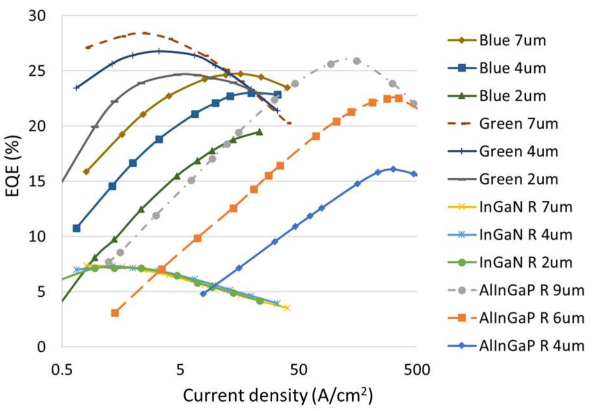

Fig. 1. EQE as a function of current density for MicroLED arrays of different material systems. The dominant wavelengths corresponding to peak efficiency are 605nm (InGaN red), 630nm (AlInGaP red), 540nm (InGaN green), and 460nm (InGaN blue).

CONCLUSIONS

We presented state-of-the-art performance of Lumileds blue, green, and red MicroLED devices based on the InGaN and AlInGaP materials systems, and also discussed manufacturing challenges. While each system has its own advantage for a given application, each emitter technology needs to be optimized for its targeted application. Moreover, the negative effects of shrinking emitter size on EQE and reliability need to be mitigated through appropriate processing methods and device architecture.

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ACRONYMS

LED: Light Emitting Diode
EQE: External Quantum Efficiency
IQE: Internal Quantum Efficiency
EXE: Extraction Efficiency
HDR : High Dynamic Range
CMOS: Complementary Metal–Oxide–Semiconductor