38.2: Invited Paper: Enabling High Resolution Photopatternable Quantum Dot Downconverters

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Enabling High Resolution Photopatternable Quantum Dot Downconverters

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Abstract

Quantum Dot downconverters can provide a scalable solution to tri-color high-resolution microLED and OLED displays by converting monochrome displays using photopatternable red and green QDs. Using internal measurements collected at NanoPattern Technologies, Inc. we model and discuss the practical wall plug efficiencies for downconverted InGaN blue microLED displays. In the range of 5 µm pixel sizes, using uncorrected 65 % film PLQY, the downconverted InGaN red emitter achieves a comparable external quantum efficiency compared to a direct red emitting AlInGaP when compared at practical current densities for microLED drivers.

Author Keywords

Quantum Dot Downconverters; Optical Density; Photolithography; Wall Plug Efficiency; MicroLED; Quantum Efficiency.

1. Introduction

One of the main challenges for micro light-emitting diode (microLED) technology is to deliver on the promised efficiency gains while shrinking pixel size to enable the dramatic cost reductions necessary for adoption. LED chips are the largest cost contributor to microLED displays, and the cost scales with the total die area. In 2021, Virey and Bouhamri projected that die sizes in the range of ⩽ 5-10 µm will be required in order to address the high-volume markets for TVs, tablets, laptops and smartphones. Furthermore, to address applications such as AR headsets, even smaller die sizes in the range of ⩽ 2 µm may be required.[1]

Most consumers focus on end user requirements such as resolution, brightness, and cost. These criteria are controlled by pixel design factors such as size and fabrication techniques. The composition, and therefore the color of LED pixels can also restrict the overall device efficiency. For conventional LED displays, the blue and green emitters are made from InGaN, while red LEDs are most commonly made from AlInGaP. Some LED makers are also developing red pixels based on InGaN technology, but currently the efficiency of AlInGaP red pixels is superior to those made from InGaN.

MicroLED efficiency considerations: The power conversion efficiency (PCE), also known as the wallplug efficiency (WPE) of an LED, is given by

$$PCE = \frac{W_{opt}}{W_{el}} = V_f E \times IE \times RE \times LEE = V_f E \times EQE \qquad (1)$$

Where W_{opt} is the optical output power, W_{el} is the electrical input power, $V_f E$ is the forward-voltage efficiency, IE is the injection efficiency, RE is the radiative efficiency, and LEE is the light-extraction efficiency. [2] The product of the injection efficiency, radiative efficiency, and light-extraction efficiency is sometimes reported as the EQE, or external quantum efficiency.

The radiative efficiency (RE) of the active region is given by the ratio of the number of photons emitted from the active region per second divided by the number of electrons injected. This can also be denoted:

$$RE = \frac{\tau_{radiative}^{-1}}{\tau_{radiative}^{-1} + \tau_{nonradiative}^{-1}} \qquad (2)$$

Where $\tau_{radiative}$ and $\tau_{nonradiative}$ are the radiative and non-radiative carrier lifetimes, respectively.

If the lifetime for a carrier to find a nonradiative recombination pathway is much larger than the radiative lifetime, RE approaches unity efficiency. However, the presence of nonradiative recombination centers increases the probability of an excited carrier in a quantum well finding a nonradiative path to recombine and lowers the RE, and therefore drops the EQE and wall plug efficiency of an LED.

One pathway for electrons and holes to recombine non-radiatively is via defects on LED sidewalls. As pixel sizes shrink, the ratio of sidewall area to LED volume increases, and the probability of an electron finding a nonradiative path for recombination through a sidewall defect increases. This leads to a lowering of EQE as the pixel size of an LED decreases. The lifetime for non-radiative recombination is determined by the lifetime of minority carriers, since the capture of majority carriers is a much more likely event than the capture of minority carriers. Because the minority carrier diffusion length is significantly larger in AlInGaP-based materials than InGaN-based materials, the loss in EQE for small pixel sizes is significantly larger for AlInGaP-based red LEDs.

Literature review of MicroLED efficiency: Because of the significant commercial importance of small pixel size microLEDs, various groups have studied this effect of pixel size on EQE for both InGaN [3-7] and AlInGaP systems [6-9]. Approaches to passivate the sidewalls to improve EQE have been studied and some improvement has been demonstrated, especially for the InGaN system. Several groups have reviewed the subject extensively, including Hsiang et al who have compiled

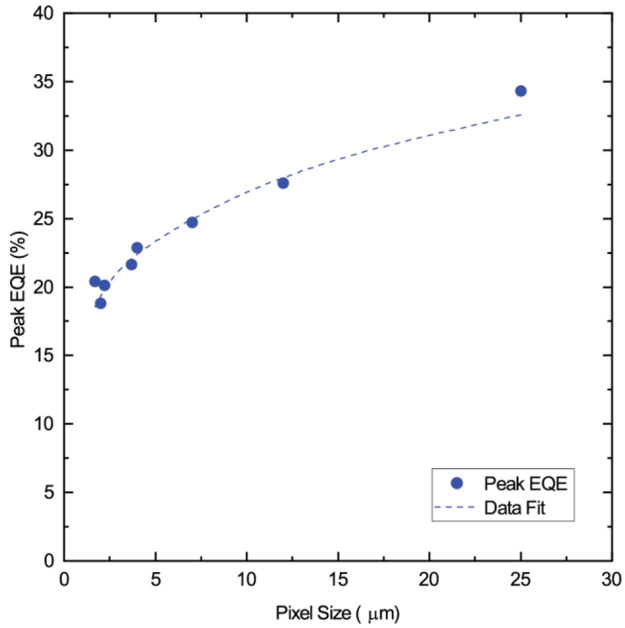

Figure 1: Peak EQE of blue InGaN microLED pixels as a function of pixel size, from [6,7].

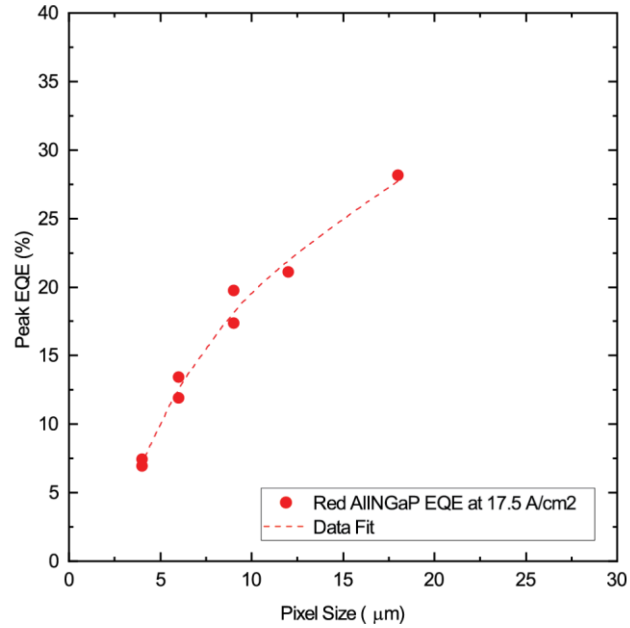

Figure 2: EQE of red AlInGaP microLED pixels at optimized drive current of 17.5 A/cm2

the peak EQE vs pixel size for red, green, and blue pixels.[8] While comparing the EQE between different pixel sizes may be challenging because the droop characteristics vs drive will change with pixel size, Hsiang [8] and Flemish [7] note that in order to achieve maximum efficiency, microLED displays can drive different microLED pixels each at their drive current corresponding to peak efficiency and use PWM to dim. However, the AlInGaP system has a peak EQE in the range of 100 A/cm^2 drive current density while the peak EQE for InGaN microLEDs is in the range of 1 (green) to 10 (blue) A/cm^2. It may not be practical for the driver backplane to drive adjacent microLEDs pixels at current densities of up to 1-2 orders of magnitude difference, with corresponding PWM duty cycles varying by 1-2 orders of magnitude as well. As a result, the practical drive current density for AlInGaP microLEDs in an RGB microLED display may be limited to ~10 A/cm^2, and the maximum EQE of red AlInGaP microLEDs will be limited accordingly. Flemish [7] suggests this practical drive condition for AlInGaP microLED pixels to be around 17.5 A/cm^2. Considering these drive conditions, the maximum EQE as a function of blue pixel size from references [6,7] have been plotted in Figure. In this case the drive condition may not be the same for each pixel size, but this is considered a practical drive condition for blue microLED pixels. Considering the maximum practical drive condition mentioned in reference [7], the EQE of AlInGaP pixels at a drive current density of 17.5 A/cm2 is shown in figure 2. This is considered to be the maximum practical efficiency of AlInGaP pixels under typical driving conditions.

Downconverted EQE Model: For low-cost manufacturing, especially for structures with small pixel pitches and sizes, it is practical to consider blue InGaN LEDs with quantum dot downconversion as an alternative to pick and place of separate red, green, and blue pixels. Due to the inherent loss of downconverting blue light to red, concerns have been raised about the efficiency of this approach. However, due to the low EQE of small AlInGaP microLEDs compared to InGaN microLEDs, it is important to weigh the downconversion loss versus the EQE loss from sidewall recombination in AlInGaP. In the case of the downconverted microLED, the inherent losses due to downconversion, from the imperfect quantum efficiency of the downconverter, and from absorption of backscattered photons must be considered. We can demonstrate an effective "total EQE" of the downconverted LED as

$$EQE_{total} = EQE_{blue} \times QD \times QE \times PE \qquad (3)$$

where QD is the quantum deficit, or the energy of the downconverted photon divided by the energy of the emitted photon, QE is the quantum efficiency of downconversion, or the probability that an excited photon is downconverted radiatively, and PE is the package efficiency of the LED, or the probability that a radiated photon will escape the package without being absorbed. For downconversion of a 460 nm blue photon to a 630 nm red photon, the quantum deficit is given by $\lambda_{blue}/\lambda_{red} = 0.73$. A package efficiency for a typical phosphor-converted white LED of 0.8 is assumed. This may be a conservative assumption if quantum dots are used for downconversion since they have a smaller scattering coefficient than the typical phosphors used in white LEDs due to their small particle size.

The effective EQE's for downconverted blue microLEDs as a function of the pixel size have been calculated from the direct microLED EQE vs pixel size given in figure 1, and the results are shown in figure 3. The effective EQE is plotted for assumptions of downconverted QE of 50% through 90%.

2. Results and Discussion

Modeled Results: In the case of red downconverted InGaN microLEDs, the expected effective EQE is equivalent to direct red AlInGaP EQE in the size range of 5-10 μm subpixels which will be necessary for cost-effective microLED displays.[1] As Augmented Reality (AR) and Virtual Reality (VR) systems begin to become higher resolution, RGB pixel sizes of 5 microns will be critical.

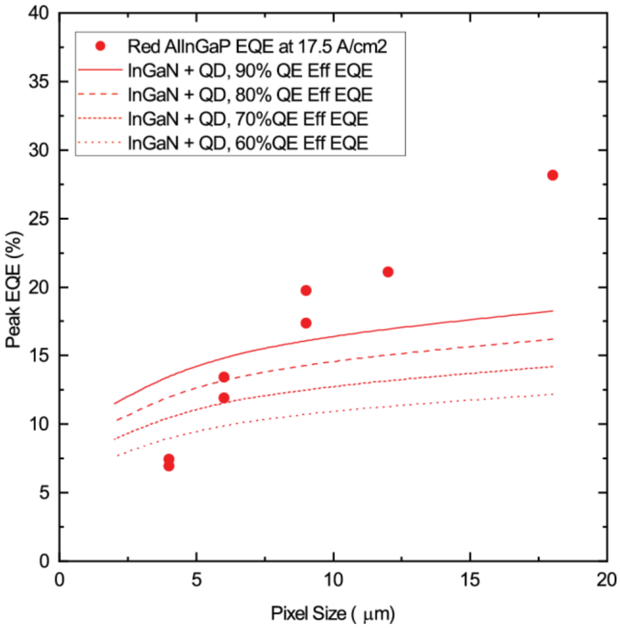

Figure 3: Modeled effective peak EQE of red downconverted InGaN pixels vs pixel size as a function of quantum efficiency of the downconverter. Data for direct AlInGaP microLEDs is replotted from Figure 2.

These will require sub-pixel sizes smaller than 1.5 microns. For the smallest subpixel sizes of 5 µm and below, it is expected that a downconverted InGaN pixel will have a higher efficiency than a direct AlInGaP pixel, up to 2x higher with high quantum efficiency downconverters. It should be noted that these numbers depend heavily on both the AlInGaP pixel efficiency as well as the InGaN pixel efficiency. Up to 1.5x higher InGaN efficiencies in this range of pixel sizes have been reported by groups at UCSB (Hwang 2017, Wong 2021). If such efficiencies can be sustained in mass manufacturing of blue microLEDs, the crossover point for higher efficiency from downconversion would increase to approximately 10 µm.

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Comparison to Experiment: As previously reported,[13] NanoPattern Technologies, Inc. is commercializing a photopatternable QD ink for high resolution display applications. Figure 3 showcases the resolution, high absorption cross section as demonstrated by a much thinner optical density of 2 at >10 µm thickness, and the >90% film Photoluminescent Quantum Yield (PLQY) values that have been demonstrated. To date, NanoPattern has measured InP/ZnS based QD films that can achieve >90% film PLQY when corrected for self-absorption or >65% film PLQY when not corrected for self-absorption. When considering device-based efficiencies, self-absorption of the emitted photons reduces the effective PLQY. It is important to note that in a reflectance measurement, the photons are counted in an integration sphere therefore all of the emitted photons are counted. Due to the isotropic emission of the downconverted photons from the QD, similar to the quantum wells, further device design efforts will be required to extract the downconverted photons towards the viewer. Common methods of light extraction include 1) index gradient matching, [14] and 2) Bragg reflectors.[15] By result, the current ideal QE for an InP based QD downconverter that has been demonstrated for sub 10 µm resolution is 65%. As of today, such

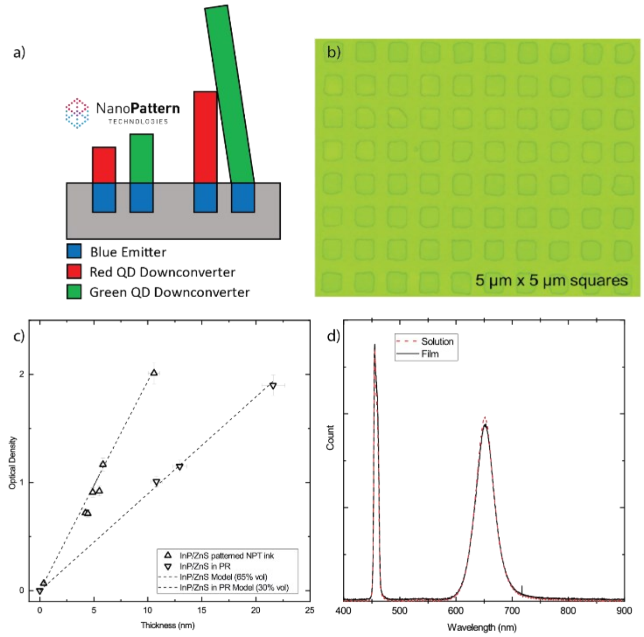

Figure 4: Argument for high absorption to reach high resolution. a) Comparison of densely packed QD downconverter film by NanoPattern and conventionally packed QD downconverters with resin and the aspect ratios at 5 um lateral resolution. b) 5 um x 5 um lateral resolution patterns using densely packed QD Downconverters. c) comparison of optical density of InP/ZnS QDs in NPT ink and conventional photoresist. d) Comparison of luminescence spectrum between QDs in solution and patterned NPT film.

a downconverter film would be able to reach equivalent EQE to direct AlInGaP emission for pixel sizes around 5-6 µm, demonstrating the viability of the approach for current microLED displays.

It is worth noting that there are many other reasons why downconversion of InGaN could be superior to fabricating three separate emitters onto a single backplane. In particular, if a blue only InGaN pixel array can be manufactured, Red and Green QD downconverter films can be patterned using parallel lithography techniques, circumventing the need for pick-and-place of three separate LED emitters. This approach can further complement approaches to growing monolithic blue emitting microLEDs.[16]

3. Impact

In this study, it was demonstrated that an InP based QD downconverter film that can be photopatterned at <10 µm lateral resolutions can reach wall plug efficiencies at or above what AlInGaP red emitters can currently achieve. At the observed QE of 65%, modeling shows that a red pixel made from QD ink patterned on a blue microLED will have equivalent EQE to a red microLED made from AlInGaP for pixel sizes in the range of 5-10 µm. As microLED technology progresses, it is important to consider all of the engineering parameters that can contribute to a practical efficiency value.

4. Acknowledgements

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