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Better but Worse, The Challenging Promise of Micro LEDs

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ABSTRACT

More than $4B have been spent over a decade to explore high-brightness, low-power MicroLED displays. The key challenge is maintaining power efficiency as MicroLEDs scale down to ~5μm. MicroLEDs scaling down results in better light extraction efficiency, but worse internal quantum efficiency. This conundrum is quantified here using physics-based models.

1 Introduction

Organic light emitting diode displays (OLEDs) now fill the globe, displaying images to more than 1 billion humans. This gargantuan capacity has led some engineers and business professionals to prophesy that inorganic light emitting diodes (μ*LEDs*) could someday become the dominant display for mobile devices owing to its lower power consumption, higher brightness, and better reliability [1-10]. The size and efficiency of μ*LEDs* are currently constrained by non-fundamental challenges, and low cost is constrained by the lack of truly massive transfer technology and the production of μ*LEDs* on small wafers. Here, the wonderful world of μ*LEDs* is described and the requirements for μ*LEDs* to become ubiquitous are enumerated.

2 The Promise of High Efficiency GaN μ*LEDs*

It is possible to generate light in semiconductor materials (such as GaN) by injecting electrons into the conduction band of the material and providing lower-energy sites ('holes') in the valence band into which they can "fall", thereby creating light of a color corresponding to the energy gap between the conduction band and valence band, also called the bandgap. A light-emitting diode is thus an electronic device integrating electrical access to the bandgap structure and allowing for efficient light generation. LEDs essentially consist of three different types of materials layered on top of each other. The first layer has a high concentration of free electrons (e.g. n −type GaN) followed by multiple alternating thin layers (1-20 nm) of material with a smaller bandgap (InGaN). The sandwiching of a smaller-bandgap material between layers of larger-bandgap material creates a well that spatially traps electrons and holes, allowing them to recombine efficiently, generating light with the wavelength of the smaller-bandgap material. Above this 'active layer', there is a layer of material with a high concentration of holes (e.g. p −type GaN). GaN was first investigated as a potential material for LEDs in the late 1960s at the Radio Corporation of America (RCA) and in later years additionally at Nagoya University in Japan and by Shuji Nakamura at Nichia Corporation. After many years of research, great advances were made by growing high-quality GaN on sapphire in 1986 and then by demonstrating p −type conductivity in GaN doped with Mg by activating the material in a post-growth anneal. These breakthroughs led to the first high-efficiency blue LEDs in 1992 (1.5% efficiency), and then to the first viable blue and green LEDs at efficiencies up to 10% in 1995. Recent developments have also yielded high brightness, yet still rather inefficient, red InGaN LEDs. Recent research has heavily focused on improving the external quantum efficiency (EQE), which is commonly defined as the product of the carrier injection efficiency (CIE), the internal quantum efficiency (IQE) and the light extraction efficiency (LEE). CIE is the ratio of electrons/holes being injected into the quantum wells to those provided by the power source. IQE is the ratio of photons generated to the number of electron-hole recombination. LEE is the ratio of photons leaving the LED to those generated. Future progress should depend on improvements in each of these areas.

3 The Promise of Higher LEE for μ*LEDs*

Jiang *et al*. were the first to recognize the benefits of using μ*LEDs* for improving LEE [11]. Here, we derived a model for LEE of planar LEDs with size D and thickness t based on ray tracing theory and inspired by the work done by Weissman for LEDs with very large D and roughened surface [12]. The model is given by the following equations. Here, $\eta_t + \eta_{st}$ represents the probability of photons escaping from the top surface of the LED, $\eta_s + \eta_{ts}$ represents the probability of photons escaping through the sidewalls of the LED. The A terms below represent the probability of photons surviving the passing through the LED semiconductor material with absorption coefficient α. The critical angle between the semiconductor material and air is θ_c. The transmission and reflection coefficients from a roughened semiconductor surface are given by T_0 and R_0.

$$LEE = \eta_t + \eta_s + \eta_{st} + \eta_{ts} \quad (1)$$

$$\eta_t \approx \frac{2DA_{it}T_0}{1 - R_0 A_t^2} \quad (2)$$

$$\eta_s \approx \frac{4\,t\,A_{is}T_0}{1-R_0^2A_d^2} \quad (3)$$

$$\eta_{st} \approx 4\,t\,A_{is}R_0A_{st}T_0 \quad (4)$$

$$\eta_{ts} \approx 4\,t\,A_{it}R_0A_{ts}T_0 \quad (5)$$

$$A_{it} = \frac{1}{D}\int_0^D\int_0^{\pi/2} \exp\left(\frac{-\alpha t}{\cos\theta}\right)\sin\theta\,d\theta\,dx \quad (6)$$

$$A_t = \int_0^{\pi/2} \exp\left(\frac{-\alpha t}{\cos\theta}\right)\cos\theta\sin\theta\,d\theta \quad (7)$$

$$A_{is} = \frac{1}{D}\int_0^D\int_0^{\pi/2} \exp\left(\frac{-\alpha x}{\cos\theta}\right)\sin\theta\,d\theta\,dx \quad (8)$$

$$A_d = \int_0^{\pi/2} \exp\left(\frac{-\alpha D}{\cos\theta}\right)\cos\theta\sin\theta\,d\theta \quad (9)$$

$$A_{st} = \frac{1}{t}\int_0^t\int_0^{\pi/2} \exp\left(\frac{-\alpha x}{\sin\theta}\right)\cos\theta\sin\theta\,d\theta\,dx \quad (10)$$

$$A_{ts} = \frac{1}{D}\int_0^D\int_0^{\pi/2} \exp\left(\frac{-\alpha x}{\sin\theta}\right)\cos\theta\sin\theta\,d\theta\,dx \quad (11)$$

$$T_0 = \int_0^{\theta_c} 2\,T(\theta)\cos\theta\sin\theta\ d\theta \quad (12)$$

$$R_0 = 1 - T_0 \quad (13)$$

$$n_s \sin\theta_c = 1 \quad (14)$$

$$T(\theta) = \frac{4\,n_s\cos\theta\sqrt{1-n_s^2\sin^2\theta}}{\left(n_s\sqrt{1-n_s^2\sin^2\theta}+\cos\theta\right)^2} \quad (15)$$

In the above equations D is the LED size, t is the thickness (height), α is the absorption coefficient in GaN at emission wavelength (~30-100 1/cm), n_s is the GaN refractive index. The simulated LEE as function of D is shown in Fig. 1 for two different LED thicknesses of 0.5 and 1 μm as a way of example. It is observed that LEE starts at ~21% for large LEDs and starts to increase with decreasing the LED size below ~10 μm; LEE ~doubles as the LED size is scaled down to 1 μm.

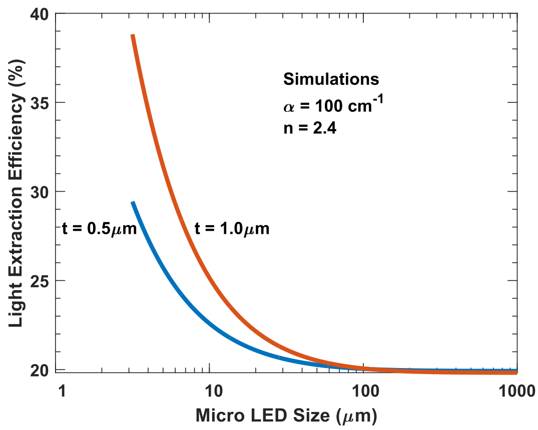

Fig. 1. Simulated light extraction efficiency (LEE) for LEDs with various lateral dimensions using equations (1)-(15). The thickness of the *μLED* t is set to 0.5 and 1.0μm. The LEE increases as the size of the *μLED* is reduced below ~50μm.

4 The Challenge of Lower IQE for *μLEDs*

Depending on the way the LEDs are fabricated, IQE for *μLEDs* can be ~50% lower than that obtained on large (~100μm) LEDs. Based on the ABC model, the internal quantum efficiency is related to the current density of the *μLED* according to the following equations:

$$\frac{1}{\eta_i} = 1 + \mu\sqrt{\eta_i J} + \frac{\gamma}{\sqrt{\eta_i J}} \quad (16)$$

$$\mu = C/B^{3/2}(q\,d)^{1/2} \quad (17)$$

$$\gamma = A(q\,d)^{1/2}/B^{1/2} \quad (18)$$

$$A \approx 70 \times (\log D)^{-s} \times 10^m \quad (19)$$

$$B \approx 3.6 \times 10^{-9}\ \times \exp(-\lambda_p/60) \quad (20)$$

$$C \approx 7 \times 10^{-31} - 7 \times 10^{-34}\lambda_p \quad (21)$$

$$m \approx 6 + \mathrm{erf}\big((\lambda_p - 525)/75\big) \quad (22)$$

$$s \approx 2.5 \quad (23)$$

where q is the electronic charge, d is the width of the quantum well, η_i is the internal quantum efficiency, A is the Shockley-Reed-Hall (SRH) recombination coefficient ($1/s$), B is the radiative recombination coefficient (cm^3/s), and C is the Auger recombination coefficient (cm^6/s). For the GaN material system, the A, B, and C coefficients were found to depend on the size of *μLED* (D) and peak emission wavelength (λ_p) in nanometers according to the empirical equations (19)-(22) above. These empirical equations were derived here based on the data reported in [13-19]:

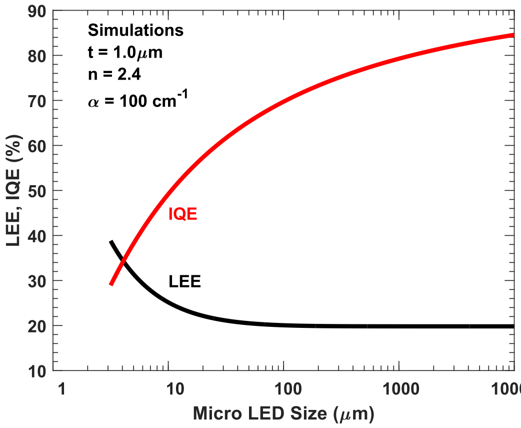

Fig. 2. Simulated LEE and IQE versus *μLED* size. IQE degrades with decreasing the *μLED* size, and the increase in LEE with smaller *μLED* size is not enough to compensate for the IQE degradation, resulting in degraded EQE at smaller LEDs as shown in [16-19].

5 The Promise of High Brightness for *μLEDs*

The calculated brightness versus current density for a blue emitting *μLED* is shown in Fig. 3 using the model given in [6]. It is observed that the luminance increases as the current density increases. It is also observed that 1-10 million nits can be dialed in with applying the right current. Such currents are much higher than those possible with OLEDs as shown in Fig. 4, where experimental $I-V$ curves for representative OLED devices [20] and Micro LED devices (this work) are shown. The OLED current is modeled using the simple, physics-based equation [21,22]

$$V \approx V_F + \frac{nk_BT}{q}\ln\left(\frac{J}{J_0}\right) + \frac{2k_BT}{q}\left(\frac{J}{J_0}\right)^{1/2} \qquad (24)$$

The *μLED* current is modeled using the simple, physics-based equation [21,22]

$$V \approx V_F + \frac{nk_BT}{q}\ln\left(\frac{J}{J_0}\right) + \frac{k_BT}{q}\left(\frac{J}{J_0}\right)^{1/2} \qquad (25)$$

where V_F is the forward voltage of the LED, J_0 is a characteristic current density that is a function of geometric and material properties of the LED, k_B is the Boltzmann constant, T is the temperature, q is the electronic charge, and n is an ideality factor. The ideal value of the forward voltage is the energy gap of the emission layer of the LED. For GaN LEDs, $J_0 \approx 0.1 - 1\ A/cm^2$, $V_F \approx 2-3V$ (depending on the emitted color), and $n \approx 1-2$. For OLEDs, typical values for the parameters are $J_0 \approx 10^{-4}\,A/cm^2$, $V_F \approx 3-4V$ (depending on the emitted color), and $n \approx 2-3$.

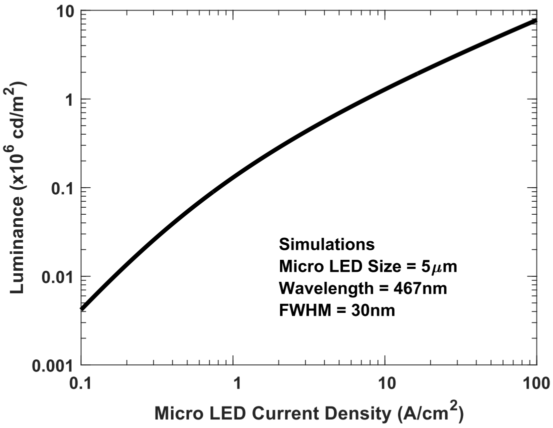

Fig. 3. Theoretical $L-J$ curve for GaN *μLEDs* showing 1-10 million nits is possible.

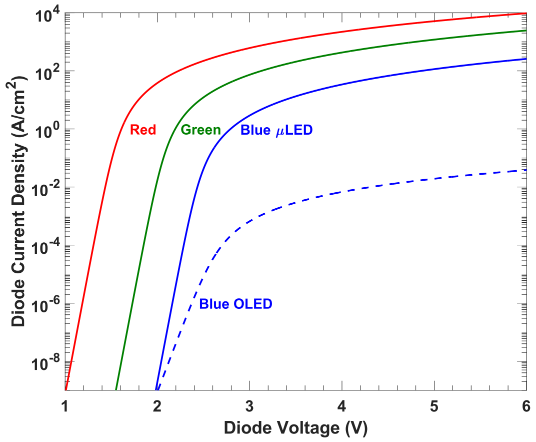

Fig. 4. $I-V$ curves for red, green, and blue *μLEDs* (this work) and a modern blue OLED [Ref. 20]. There exists a fundamental gap between the current carrying capability of inorganic *μLEDs* and OLEDs (~10,000x). The lines are best fits to experimental data (not shown here for clarity).

6 Conclusion

μLED display is a rapidly rising star on the horizon of mobile displays. This emissive display promises exceptionally high brightness and low power consumption and has already revealed a cornucopia of new engineering challenges. For example, for *μLED* displays to be viable, the size of *μLEDs* needs to scale down to ~5μm. This scale down results in improvement in light extraction efficiency but reduction of internal quantum efficiency. Here, the improvement in LEE and degradation in IQE have been calculated using intuitive physics-based models. These models provide estimate of target improvements required in IQE to meet the EQE requirements for low-power display applications. Moreover, theoretical modeling of $I-V$ curves of OLEDs and *μLEDs* has revealed that *μLEDs* have much higher current carrying capability supporting the hypothesis that *μLEDs* are much brighter than OLEDs.

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