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Micro-LEDs: from Device Physics to Novel Displays

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ABSTRACT

Micro-LED display requirements are pushing LED technology into uncharted territory. We discuss the properties of the two main LED material families, review the latest progress in understanding their device physics, and explain what challenges lie ahead to enable novel displays.

1 Introduction

Micro-LEDs (uLEDs) are widely expected to enable a broad class of future displays, including giant TVs, smart phones / watches, and AR/VR systems. Compared to other display technologies, they promise improved efficiency, increased brightness with good reliability, very high resolution… However, significant challenges lie ahead before such promises can be fulfilled; and, while a few commercial uLED products already exist, years of effort will be necessary to unleash their true potential.

In this manuscript, we focus on the LED technology itself, leaving aside the equally-important discussion of assembling/transferring uLEDs into a display. We introduce the properties of the main semiconductor families used in LEDs, and discuss recent findings and future challenges in uLED technology.

2 Semiconductors for light emitters

There are two main semiconductor families involved in uLED technology: GaAs-based and GaN-based. Here, we shortly review their history and well-known properties, in the context of standard LEDs (*i.e.* of regular dimensions).

2.1 Long-wavelength: legacy III-V's (GaAs & AlInGaP)

GaAs-based LEDs have seen decades of development, starting with basic research in the early 60s. In the 70s, the industrialization of these LEDs ramped up, led by companies including Hewlett-Packard and Monsanto. Over this period, their emission wavelength was extended from infrared to red and finally yellow-orange. Significant technical progress was achieved in the 80s and 90s, including better epitaxy tools leading to better materials; the nanometer-scale control of epitaxial layers; and optimized LED geometry letting the light can escape the semiconductor. These led to a sharp rise in the efficiency of red LEDs, up to tens of percent of external quantum efficiency (EQE) – propelling them from niche applications to the most efficient long-wavelength emitters [1].

Over time, the material for red emission switched from GaAs itself, to AlInGaP grown on a GaAs substrate. For simplicity, we designate all such LEDs as GaAs-based.

Today, GaAs-based LEDs reach an EQE above 70% at deep-red wavelengths. At shorter wavelengths – especially for yellow LEDs– the efficiency remains much lower. This is a rather fundamental effect, caused by the semiconductor band structure. In addition, GaAs-based LEDs display a somewhat pronounced roll-off in efficiency at high temperature; again, this is governed by the band structure (namely, the lack of carrier confinement in short-wavelength quantum wells). In summary, GaAs-based red LEDs are excellent red emitters, but there remain some challenges in maintaining this efficiency at short wavelength and high temperature.

2.2 Short-wavelength: III-Nitrides (GaN / InGaN)

The 90's saw a revolution in optoelectronics, when several teams in Japan demonstrated how GaN could be used to make efficient blue LEDs and lasers. The key breakthroughs included: achieving sufficient material quality, despite growing GaN on a mismatched substrate that results in a high defect density; learning how to grow p-type GaN and make it electrically active; and progress in epitaxy equipment and techniques for growing high-quality InGaN layers, to tune the emission wavelength in the visible range. This seminal series of discoveries was ultimately awarded the physics Nobel Prize in 2014.

Compared to legacy GaAs-based semiconductors, GaN is less mature and stands out in several aspects:

(1) a still-high defect density which requires particular care in epitaxy [2]
(2) a large strain in light-emitting InGaN layers (especially at long wavelength), causing significant material challenges
(3) the presence of inherent megavolt-scale electric fields across the light-emitting layers, which dominates the device physics [3]
(4) the need for novel light extraction approaches, due to the distinctive optical properties of GaN [4]

Despite these challenges, the strong economic push of the solid-state lighting market over the last two decades led to the development of violet and blue LEDs with near-ideal efficiency. [5, 6].

In principle, GaN-based LEDs can cover a very wide wavelength range, from the deep-UV to the infrared. In practice, however, this come with significant challenges in materials science – for instance, the high strain in InGaN layers emitting at long-wavelength. This has so far restricted their wavelength range of operation. Initially, most focus went to the development of blue LEDs, whereas green LEDs remained somewhat inefficient. Then, over the 2000's, progress in epitaxy and device design enabled commercial green LEDs with tens of % of EQE. Nonetheless, maintaining a high EQE at long wavelength (especially beyond the green region) remains a significant challenge.

2.3 The "green gap"

Due to the inefficiency of short-wavelength GaAs-based LEDs and of long-wavelength GaN-based LEDs, the spectral region in the green-to-orange range (roughly, 520 nm to 600 nm) is especially challenging. This has caused a lack of good LEDs in this region, an effect known as the "green gap" and illustrated in Fig. 1. However, as we will discuss later, the status of this challenge is quickly evolving.

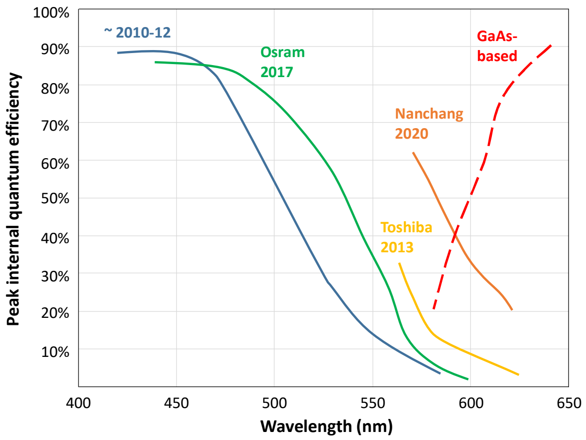

Fig. 1 Evolution of the green gap. Full lines: efficiency of GaN-based LEDs over time. Dashed lines: GaAs-based long-wavelength LEDs. A decade ago, the green gap was pronounced; it is now slowly closing. After data from [15-18]

3 Recent findings in device physics and implications for uLEDs

The previous discussion describes mainstream knowledge of the main III-V semiconductor families. We now review more recent findings in device physics that are of importance for uLEDs.

3.1 Size effects

Sidewalls (i.e. surfaces "cutting through" the light-emitting region of an LED) are known to be a concern for efficiency. This is because the sidewall atoms can form "dangling bonds" that are prone to non-radiative recombinations. For conventional LEDs, this issue was tackled in the 90s when researchers at Hewlett-Packard developed pyramid-shaped LEDs (for efficient light extraction) and had to maintain sufficient sidewall quality [7].

However, this challenge has become much more significant for uLEDs. Due to their small dimensions, any deleterious effect from the sidewalls is enhanced. Accordingly, various groups have tackled the issue of maintaining efficiency for very small devices.

Many studies focused on blue GaN-based LEDs. In 2017, it was shown that devices as large as 200 μm could already suffer from sidewall recombinations [8]. This might seem surprising, given that electrons are often believed to be localized on a nm-scale in GaN-based LEDs. However, it was recently revealed that electrons can indeed diffuse laterally for tens of μm [9], which explains such size effects. Over the last few years, several teams have shown that proper surface passivation of the sidewalls by a dielectric layer could largely suppress sidewall recombinations. This has pushed the "cliff" in efficiency to smaller and smaller devices [10-12]. Recent results indicate that devices as small as 6 μm can be protected from size effects, and further progress is plausible.

GaAs-based red LEDs have been the subject of fewer publications, however, it is clear that sidewall recombinations are much more problematic in this material system. For instance, researchers at UCSB recently applied a similar passivation scheme as in GaN-based LEDs but found a much more severe efficiency drop. Indeed, at 20 μm size, GaN LEDs suffer nearly no sidewall loss, whereas GaAs-based LEDs see a ~50% reduction in efficiency [13]. Therefore, future improvements will be needed, especially for the smallest GaAs-based uLEDs. It remains open-ended whether such progress will come from empirical optimization of passivation techniques, or will also require a deeper understanding of the underlying physics of sidewall recombinations.

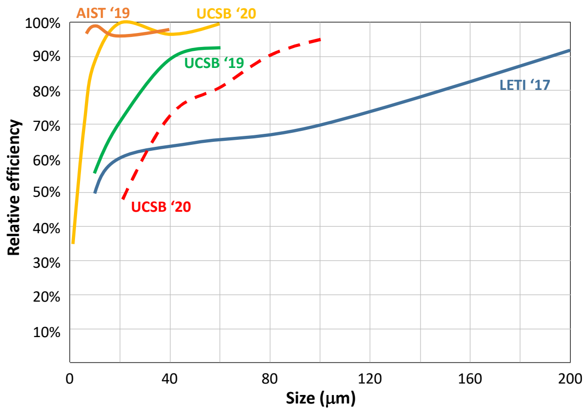

Fig. 2 Drop in efficiency for small-size uLEDs. Solid lines: GaN-based blue LEDs, showing significant improvements at small size over time. Dashed line: GaAs-based red LED, which still suffer from significant size effects, even with good passivation. After data from [10-13]

Fig. 2 summarizes the works mentioned above: it shows a steady improvement over the years in the case of GaN-based LEDs, and a relatively-less mature status for GaAs-based LEDs.

3.2 The challenge of red emission

3.2.1 Revisiting the green gap in GaN LEDs

As previously mentioned, GaN-based LEDs have historically suffered from suppressed efficiency at long wavelength. However, the last decade has seen significant progress, with several teams achieving breakthroughs at longer and longer wavelengths. Fig. 1 shows the evolution of the green gap over the last decade. Given such improvements, the term “yellow gap” would now be more appropriate.

This evolution stems from the combination of various developments. First, there has been progress in growing high-quality GaN-based materials. This was foremost enabled by better epitaxy tools and a better know-how acquired over the years, but was also supported by a better physical understanding of what type of defects actually matter in GaN-based LEDs [2] and how they might impact long-wavelength efficiency [14].

Second, a number of teams have proposed solutions to reduce the material strain in long-wavelength InGaN layers – including the work of [17] and many others. Such approaches are still in their early days, and may lead to further breakthroughs.

3.2.2 Which emitter for red?

Several technologies are now contenders for red uLEDs, each carrying various advantages and risks:

(1) “conventional” GaAs-based LEDs, which are more mature but suffer most from size-reduction effects
(2) InGaN-based red LEDs, which are very challenging from a materials standpoint and still at an early development stage
(3) Color-converted LEDs, which use an InGaN blue LED and a red quantum dot converter, but present challenges in optical efficiency and quantum dot reliability

Which path will prevail remains a key open question in uLED technology. The respective pros and cons of each approach will probably make them suitable for different uLED applications – depending on the relative importance of the uLED size, brightness, reliability etc…

3.3 Light extraction challenges

Conventional LEDs, whether GaAs- or GaN-based, have achieved very high light extraction efficiency over time. This was enabled by a variety of techniques, including geometric shaping [7]; the inclusion of photonic structures [19]; and scattering by random [20] or organized [21] micron-scale features. In addition, the industry has harnessed materials with the lowest optical loss (e.g. Ag-based contacts with high reflectivity).

Such solutions need to be revisited for uLEDs in view of new challenges:

(1) Light-extracting features with several um in size are commonly used but cannot fit in a uLED
(2) Some of the best optical materials present reliability risks when combined with large sidewall areas
(3) The emphasis is not only on high extraction but on high brightness, precluding the use of standard approaches like high-index dome encapsulation
(4) The directionality of emission matters in many display applications

While light extraction is a crucial topic to enable high-efficiency uLEDs, published results on the topic remain scarce. Modeling work [22] has shown how the details of the uLED’s geometry can have an important impact, as shown in Fig. 3. Yet, such work often remains based on optical raytracing. Given the dimensions of the smallest uLEDs, the relevant framework is actually at the frontier between geometric and wave optics, which leads to a challenge both conceptually and in the availability of modeling tools. True innovation on this topic is likely to emerge in the coming years.

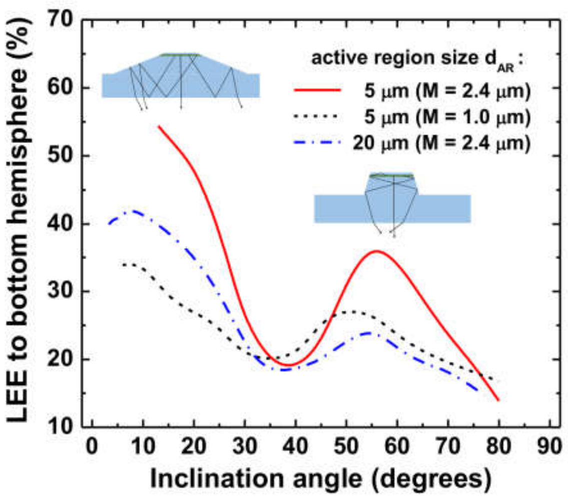

Figure 3 Modeled effect of a uLED’s shape on the light extraction efficiency, in a geometric-optics framework, showing the existence of ‘preferred angles’. Reprinted from [22] under CC license.

4 Conclusions

The two main material families used for short- and long-wavelength LEDs have achieved significant maturity over the last decades, primarily driven by the needs of solid-state lighting. However, uLED displays call for a reconsideration of standard LED technology. Some of the new key challenges are the drop in efficiency for small devices, the lack of efficient red uLEDs, and difficulties in extracting light with conventional techniques. A continued exploration of device physics and material science is likely to drive future progress on the road to disruptive uLED displays.

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