A
PROJECT REPORT
ON

Recent Progress in Micro-LED-Based Display Technologies

By

Harsh Bokadia 2021A3PS2592H
Dhyey Rajyaguru 2020A8PS2148H

Under the guidance of

PROF. PK PATTNAIK

BIRLA INSTITUTE OF TECHNOLOGY AND SCIENCE, PILANI (Rajasthan)

(Apr, 2024)

Acknowledgements

We want to express our profound thanks and gratitude to Prof. PK Pattnaik for allowing us to delve deeply into fibre optic sensors through this project. We are also thankful for his guidance, encouragement and helpful critiques of this research work.

Birla Institute of Technology and Science-Pilani, Hyderabad Campus

Certificate

This is to certify that the project report entitled “Recent Progress in Micro-LED-Based Display Technologies” submitted by Mr Dhyey Rajyaguru (ID No. 2020A8PS2148H) and Mr Harsh Bokadia(ID No. 2021A3PS2592H) in partial fulfillment of the requirements of the course EEE F426, Fiber Optics and Optoelectronics, embodies the work done by them under my supervision and guidance. Date: (Prof. P.K. Pattnaik) BITS-Pilani, Hyderabad Campus.

Date: 28/04/2024

(Prof. P.K. Pattnaik)
BITS- Pilani, Hyderabad Campus

Table of Contents

Abstract

This report reviews the article “Recent Progress in Micro-LED-Based Display Technologies” by Abdur Rehman Anwar and Dr. Muhammad Tariq Sajjad. The paper, first published on 7 April 2022, discusses the wave of microlight-emitting diodes as a better alternative to primitive sources. Earlier, CRT displays were prominent in the world. However, their efficiency and quality were relatively low. Further developments made LCD technology a better alternative; however, even in its most efficient form, two-thirds of the incident light used to get wasted. Micro-LEDs were considered a much better option with the increasing demand for high-performance displays in virtual reality, augmented reality, and 3D projection. This was because of its promising features, like low power consumption, wider colour gamut, longer lifetime, and rapid response times, positioning them as potential successors to traditional liquid crystal and organic LED displays. However, their mass transfer processes and manufacturing costs are a challenge, and this report on the review paper explores various mass transfer display technologies and colour conversion strategies to adopt to have high-resolution and transparent displays.

Introduction

From the invention of the cathode ray tube (CRT) to the most recent developments in micro-LEDs, display technology has transformed our everyday lives through various uses, including televisions and medical equipment. With their superior response times and visual depth, CRTs ruled the market for decades, but the advent of liquid crystal displays (LCDs) in the 2000s brought with them portability and energy economy. Despite its advantages, the development of organic light-emitting diodes (OLEDs) in the 1990s was prompted by persistent problems with LCDs, such as colour saturation and response time. Because of their versatility and power-saving qualities, OLEDs were used in intelligent electronic items; nonetheless, issues with colour purity and device longevity arose.

Micro-LEDs have recently attracted much attention in display technology because of their superior qualities over LCDs and OLEDs, such as reduced power consumption, longer lifespan, and more comprehensive colour range. Improvements in light extraction methods and luminescence efficiency have allowed for advances in micro-LED technology. Micro-LED-based displays have been shown by companies including Sony, LG, and Samsung, indicating a technological revolution. Additionally, introducing micro-LED panels by businesses such as PlayNitride and X-Celeprint demonstrates increasing market interest. Phosphors have historically been the primary source of colour conversion for full-colour micro-LED displays; however, new advancements have led to the introducing of quantum dots (QDs) and nanoparticles as substitutes. Micro-LEDs are used in high-speed visible light communication in addition to displays.

However, due to difficulties with epitaxial growth, switching from LEDs to micro-LEDs frequently leads to efficiency deterioration. Resolving these issues and refining mass manufacturing methods are essential if micro-LED technology is to be widely used. In addition, more investigation is required to thoroughly investigate the possibilities of QD-based colour conversion and overcome related obstacles.

A rapid drop in efficiency is typically observed when devices get smaller, going from LEDs to micro-LEDs. In this review, we evaluated several technologies for the mass manufacturing micro-LEDs. We talked about the issues related to the epitaxial growth of micro-LEDs, which causes these efficiency degradations. We also discussed the advantages and disadvantages of QD- and phosphor-based colour conversion methods for full-color display. In conclusion, we enumerated a few well-known tactics that may prove beneficial in resolving issues related to colour conversion technology.

Epitaxial Growth and Chip Processing of LEDs

The transition from conventional LEDs to micro-LEDs is the article's main topic, which offers a thorough review of the development and difficulties facing III-V-based LEDs. It examines the benefits and drawbacks of employing silicon and sapphire substrates in epitaxy and the increasing need for larger wafer sizes. The paper highlights the effects of mesa size reduction on epitaxial growth and device performance while discussing the fabrication techniques of conventional LEDs and micro-LEDs.

The efficiency decline in micro-LEDs is critically analysed and attributed to sidewall effects and increased fault density. The review addresses methods to eliminate surface imperfections, minimise sidewall recombination, and thermal annealing to enhance micro-LED performance. It contrasts micro-LEDs' efficiency based on InGaN and AlGaInP, emphasising the latter's practically size-independent efficiency due to reduced surface recombination.
It offers insightful information about the difficulties and potential fixes for improving the functionality of micro-LED technology. It highlights how crucial it is to fully resolve sidewall effects and epitaxial challenges to utilise micro-LEDs in upcoming display applications.

Figure 1. presents a comparison of the EQE and chip size, demonstrating that the EQE decreased from approximately 10% to 5% as a result of the chip size decreasing from 500 µm × 500 µm to 10 µm × 10 µm. Many approaches to solving this problem are mentioned. A selection of them are presented here. For example, Chen et al. reported on pyramidal micro-LEDs, wherein the use of SiO2 current confinement layer reduced reverse current leakage by a factor of two, as illustrated in As a result, the light output power was increased by almost double. The SiO2 layer was introduced by Wong et al. for sidewall passivation, resulting in a 37.5% improvement in the EQE of micro-LED (with a dimension of 20 µm x 20 µm

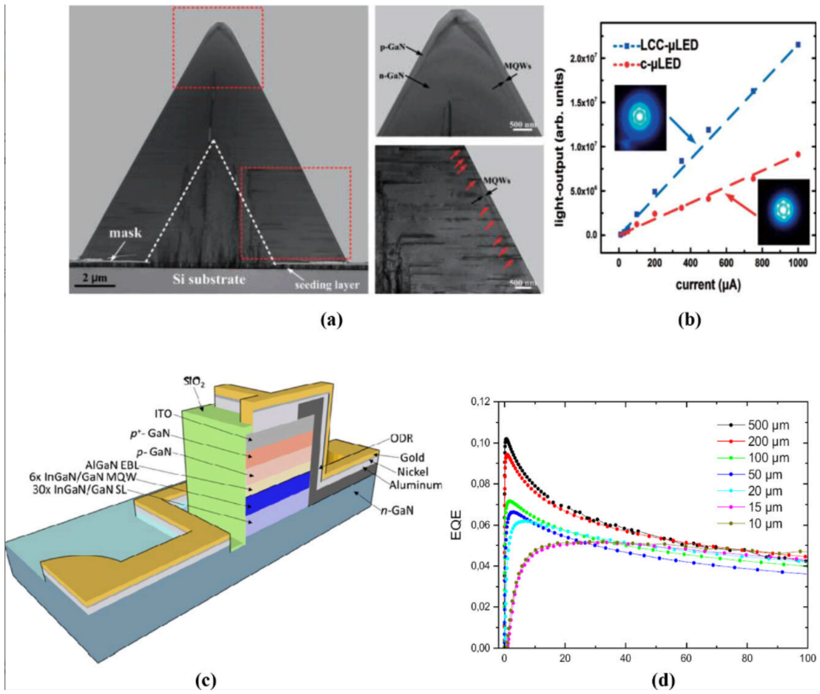
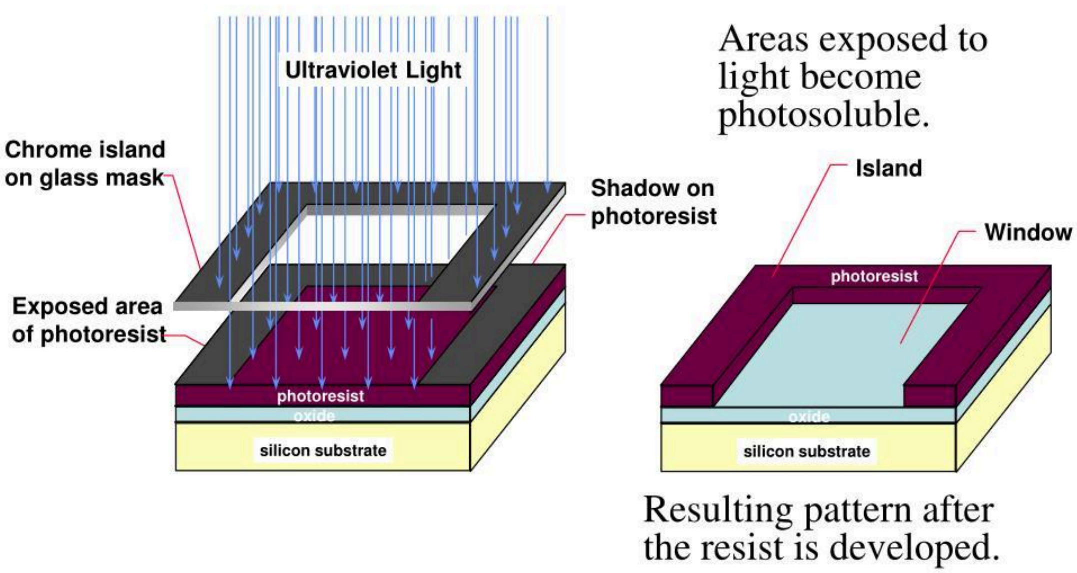

p-GaN
n-GaN
MQWs
500 nm
mask
Si substrate
seeding layer
2 μm
(a)
LCC-μLED
c-μLED
light-output (arb. units)
current (μA)
(b)
SiO2
ITO
p⁺- GaN
p- GaN
AlGaN EBL
6x InGaN/GaN MQW
30x InGaN/GaN SL
ODR
Gold
Nickel
Aluminum
n-GaN
(c)
500 μm
200 μm
100 μm
50 μm
20 μm
15 μm
10 μm
EQE
(d)

Fig 1


Ultraviolet Light
Chrome island on glass mask
Shadow on photoresist
Exposed area of photoresist
photoresist
oxide
silicon substrate
Areas exposed to light become photosoluble.
Island
Window
photoresist
oxide
silicon substrate
Resulting pattern after the resist is developed.

Assembling Technologies for Mass Production of Micro-LEDs Display

Despite its fantastic performance, the commercial production of micro-LED technology is confronted with significant hurdles. Significant problems such as full-colour realisation, mass transfer of micro-LED chips, and monolithic fabrication have hampered successful mass production. Since inorganic LED wafers are usually between 4 and 8 inches in size, mass transfer technology is required to transfer LED arrays to a receiver substrate to construct large-area micro-LED displays. Several methods have been used, each with pros and cons that may affect display performance, such as pick and place, selective release and transfer, and self-assembly. For instance, dependable technology necessitates the loss of over 2488 pixels during transmission to achieve a 3840 × 2160 × 3 micro-LED full-colour display with 4K pixels per inch. To enable effective transfer, businesses have developed electrostatic, van der Waals, laser-based, and fluidic-based assembly strategies. These endeavours aim to surmount the obstacles linked to large-scale manufacturing and facilitate the extensive integration of micro-LED technology across diverse uses.

Various Mass Transfer Technologies

1. Laser-based

Transfer yield 99.99%. The transfer rate is ≈100 million per hour.
Performance
Advantages: No impurities transfer on the substrate surface.
Disadvantages: Laser source can damage their transfer stability.
Chip size:>1 µm
Used by companies: Optovate/Uniqarta

2. Electrostatic

Performance:≈1 million per hour.
Advantages: Flexible to use and have perfect repeatability.
Disadvantages: Due to electrostatic, the charges are induced, which can degrade device performance
Chip size:1–100 µm
Used by companies: Apple/Luxvue

3. Fluidic-based assembly

Transfer method:
Performance:≈50 million per hour.
Advantages: Economical
Disadvantages: Inefficient, the probability of pixel damages during transfer is high.
Chip size:>20 µm
Used by companies: Foxconn/eLux

4. Roll-to-Roll/R2R

Transfer method:
Performance:≈10 000 per second.
Advantages: Economical, high efficiency and high throughput
Disadvantages: The probability of device damage is high.
Chip size:≈less than 100 µm
Used by companies: Korean Institute of Machinery and Materials [

The review provides an insightful analysis of various mass transfer technologies utilised in producing micro-LEDs, addressing their advantages, challenges, and potential applications. It covers electrostatic-based, laser-based, elastomer stamp-based, fluidic-based, and roll-to-roll transfer methods, highlighting their mechanisms and achievements in micro-LED assembly.

The electrostatic-based approach, pioneered by LuxVue (owned by Apple Co.) in 2012, employs an electrostatically charged transfer stamp to pick up micro-LEDs from a host substrate and transfer them to a receiving substrate. While flexible and selective, careful voltage control is crucial to prevent damage to micro-devices.

Laser-based transfer techniques, such as laser-induced forward transfer and massively parallel laser-enabled technology (MPLET), utilise laser beams to detach and transfer micro-LEDs. Uniqarta introduced MPLET in 2013, demonstrating high-speed and parallel transfer capabilities with minimal placement errors.

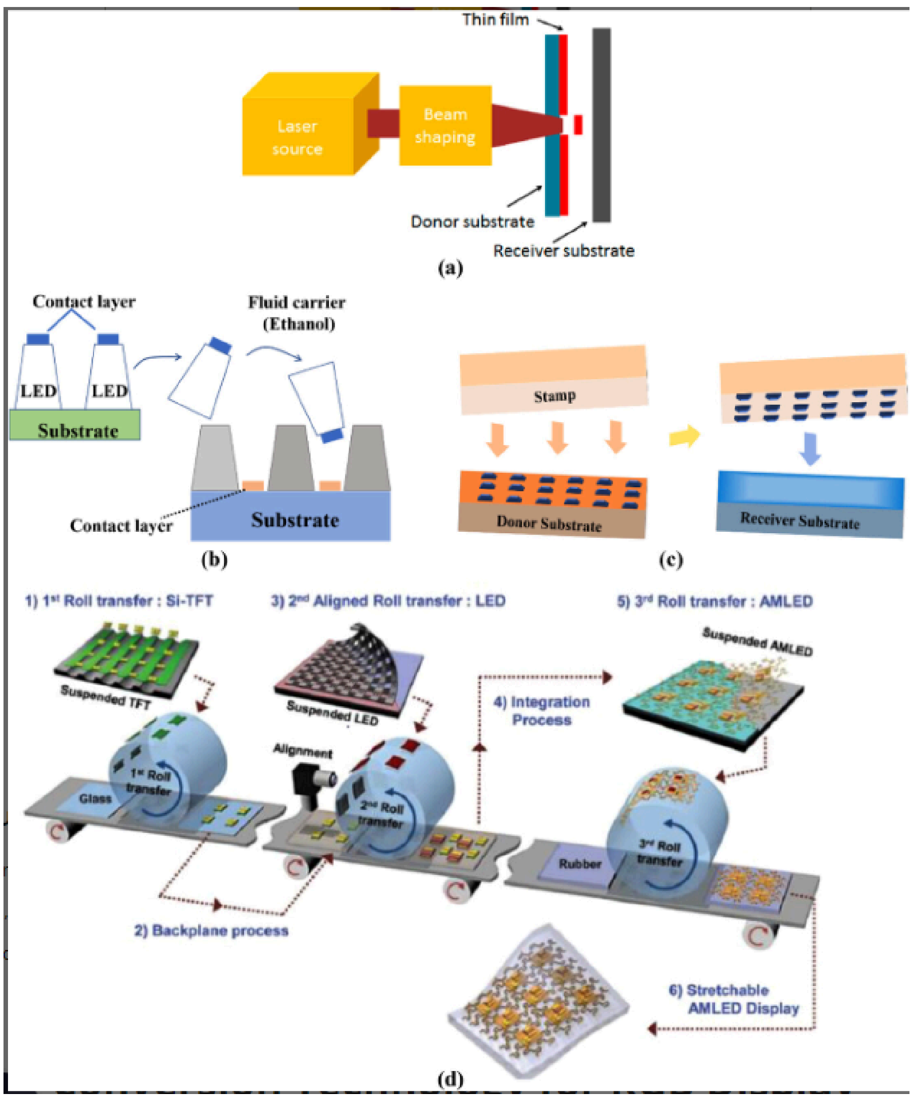
Various companies like the Rogers group have developed Elastomer stamp-based methods, including micro-transfer printing technology (μTP). These methods leverage differences in adhesion between the stamp and substrates to transfer micro-LEDs. While effective for curved screens and wearables, challenges related to repeatability have been reported. Solutions such as magnetorheological stamps and optimisation techniques have been proposed to enhance performance.

Fluidic-based assembly, a cost-effective approach, offers high throughput and low interconnection parasitic effects. Companies like Saeedi et al. have successfully transferred micro-LEDs using this method, although further development is needed for commercial applications.

Roll-to-roll transfer, developed by the Korean Institute of Machinery and Materials (KIMM), provides high-speed and continuous micro-LED transfer for lightweight and flexible displays. While promising, challenges related to precision and reliability remain.

Overall, elastomer stamp-based transfer methods show promise due to their high transfer yield, while laser-based and electrostatic technologies offer good repeatability. However, roll-to-roll transfer holds potential for large-scale micro-LED production due to its high throughput. Further research and development are needed to optimise mass transfer technologies for commercialisation in micro-LED display applications.

The figure shows all the different methods:

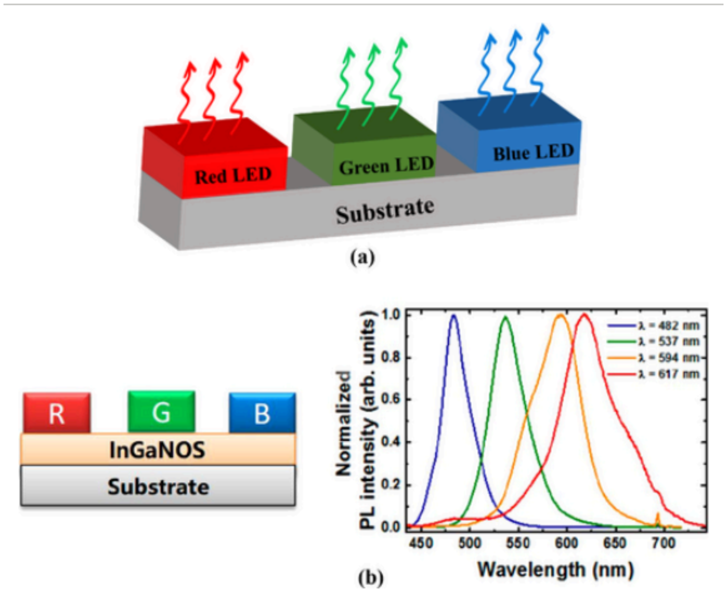


Color Conversion Technology for RGB Display

The review highlights the switch from single-colour LEDs to RGB displays and discusses the difficulties in producing full-colour micro-LED displays. While liquid crystals and colour filters are used in LCD technology to create colour, micro-LED displays need exact control over biases to adjust the emission of individual LEDs.

Materials from the III-V group, such as InGaN/GaN, are typically used for monochromatic LED emissions. However, generating full-colour displays from single-colour LEDs poses a significant difficulty for researchers. Because of strain-related problems and defects brought on by the lattice mismatch between the InGaN and GaN layers, the luminous efficiency of green and red LEDs is noticeably lower than that of blue GaN-based LEDs.

Several solutions are investigated to tackle the problem of achieving emissions in the green and red spectral areas. These include exploiting GaP/GaAs-based LEDs for red-light emission or utilising the quantum-confined Stark effect (QCSE) in InGaN/GaN quantum wells (QWs) to induce a redshift in light emission. Nonetheless, variations in the material systems used in the blue, green, and red LEDs can affect important variables and RGB display performance. Strategies used to overcome these obstacles include tailored substrates, bandgap engineering, and optimum growth conditions. For example, strain in InGaN QWs is reduced by employing metamorphic InGaN buffer layers or InGaN pseudo-substrates, improving indium incorporation and material quality. Additionally, red InGaN micro-LEDs with an emission wavelength of 632 nm have been demonstrated using porous GaN pseudo-substrates.



METHODS FOR COLOR CONVERSION

An excitation source like blue or UV micro-LEDs and colour converters such as phosphors or quantum dots are essential for achieving full-colour displays. UV micro-LEDs require red, green, and blue colour converters, while blue micro-LEDs only need red and green converters. However, accurately depositing colour converters onto LED pixels poses a significant challenge. Various printing technologies have been explored, including aerosol jets, inkjets, stamping, and coating techniques like spin-coating, pulse spray, and mist. Among these methods, aerosol jet printing stands out due to its non-contact nature, precise deposition capabilities, and ease of handling viscous inks.

The various methods are:

1. Phosphor-Based Color Conversion

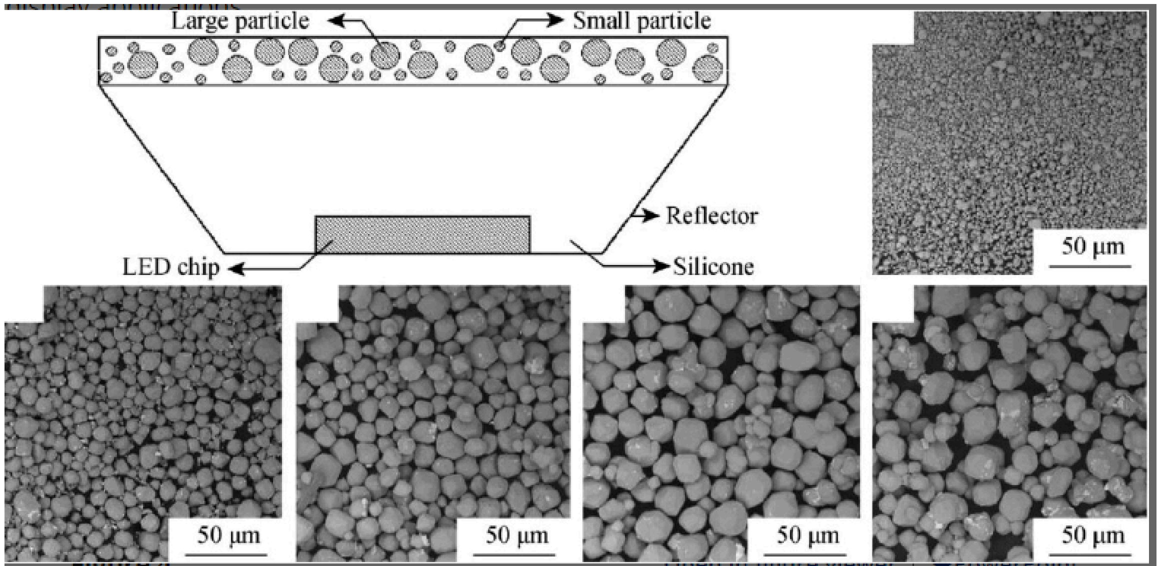
The prominent features of phosphors-based conversion technology are:

i) high quantum yield, which is approximately more than 80%

ii) high thermal stability, which is approximately above 150°C

iii) high resistivity for the moisture (chemically stable), iv) fast-luminesce decay and very stable emission spectrum under the irradiation of continuous light flux.

Because of these features, it is widely used to generate white light for lighting applications. In phosphor-based LED displays, various phosphor materials, such as $Ca_{1-x}Sr_xS$: Eu^{2+}, $Sr_2Si_5N_8$:Eu^{2+}, and $SrGa_2S_4$:Eu^{2+}, are frequently used to produce red and green emissions. Phosphorus mixtures such as $LiCaPO_4$:Eu^{2+} and $Sr_5(PO_4)_3Cl$: Eu^{2+} are also used to generate blue light. Another method uses phosphors to turn blue light from micro-LEDs into white light, combined with colour filters to produce full-colour displays. However, because the colour-conversion filters scatter light, this technique may result in crosstalk between sub-pixels. Different deposition methods are investigated to cover every pixel with phosphor layers to solve this.
The achievement of consistent colours in screens dramatically depends on the phosphor particle size. Phosphor particles range in size from nanometers to micrometres, depending on the procedures used in their manufacture. While smaller particles improve colour uniformity, they also decrease light conversion efficiency. Chen et al. suggested combining small (4 µm) and large (22 µm) phosphor particles in the color-conversion layer in a 3:2 ratio to balance efficiency and uniformity. This method preserves a respectable light conversion efficiency while improving colour consistency. Alternative materials, such as quantum dots, are still being investigated because of their high efficiency and tiny size, which could lead to significant breakthroughs in display technology.


Large particle
Small particle
Reflector
LED chip
Silicone
50 μm
50 μm
50 μm
50 μm
50 μm

Reference I - Funnel Tube Array

Micro-LED displays, which provide vivid images and energy economy, have emerged as a promising challenger in the constantly changing field of display technology. Like any innovation, they are not without difficulties, though. The efficiency and color accuracy constraints of the traditional color conversion materials used in Micro-LED displays are one such obstacle. The innovative solution that follows is the Funnel-Tube Array structure.

Fundamentally, an array of small light-emitting diodes powers micro-LED displays, enabling them to show images. But in order to achieve full-color representation, color conversion materials must be used, and these materials frequently have low optical densities, which causes inefficiencies and problems with color blending known as crosstalk. In order to address these issues head-on, the Funnel-Tube Array topology greatly increases optical efficiency and removes color crosstalk.

What is the Funnel-Tube Array structure, therefore, and how does it function? Imagine this: an array of carefully crafted funnel-shaped tubes sits atop a layer of micro-LEDs that forms the base. Every tube is properly positioned in relation to a subpixel, guaranteeing a smooth combination of color conversion and light emission. Phosphors, which are found inside these tubes, are in charge of turning the light that micro-LEDs output into white light, which is an essential step toward obtaining full-color displays.

The inner surface of these funnel-shaped tubes can be adjusted to either reflect or absorb light, which is where the creativity of the Funnel-Tube Array arrangement really shows itself. Because of its adaptability, light propagation may be adjusted, improving efficiency and color accuracy even more. In addition, the structure removes phosphors by separating them inside each subpixel region.

The advantages don't end there, either. Another problem with the Funnel-Tube Array form is ambient light reflection, which is a common annoyance in display contexts.

Unwanted reflections are reduced through the careful placement of guiding light inside the tubes, making for a cleaner, more engaging visual experience.

The Funnel-Tube Array structure has been shown to provide notable gains in performance through simulation experiments. It not only significantly lowers color crosstalk but also increases light conversion efficiency, opening the door for displays that use less energy. Furthermore, the construction guarantees the best possible image quality even under a variety of lighting circumstances by reducing reflections from ambient light.

This invention has considerably more ramifications than just improvements in technology. Imagine panels that are not only more visually stunning but also run more sustainably, drawing less power and producing better quality images. The Funnel-Tube Array structure has the potential to completely change how we interact with visual content in a variety of applications, including digital signs, augmented reality, and smartphones.

The Funnel-Tube Array construction is an attractive solution in the field of consumer electronics, where there is a constant desire for gadgets that are lighter, thinner, and more energy-efficient. Manufacturers can develop thinner, more immersive displays without compromising performance by improving color accuracy and maximizing the use of light.

Moreover, this breakthrough has an impact not only on consumer electronics but also on industries like entertainment, automobile, and healthcare. Imagine immersive entertainment experiences that take viewers to new worlds of reality, car displays that adjust flawlessly to changing lighting conditions, and medical monitors with unmatched color accuracy—all made possible by the Funnel-Tube Array construction.

Like any technological breakthrough, there are several obstacles in the way from research to broad implementation. There are challenges to be met, ranging from streamlining production procedures to guaranteeing interoperability with current display technology.

For customers, producers, and academics alike, the Funnel-Tube Array construction is a worthwhile investment because the potential benefits greatly exceed the challenges.

The Funnel-Tube Array topology in Micro-LED display technology is a paradigm change. Key issues including color accuracy, efficiency, and ambient light reflection are addressed, opening the door for a new breed of displays that are not only aesthetically pleasing but also adaptable and low-impact on the environment. Innovations like the Funnel-Tube Array construction serve as a constant reminder of the transformational power of human ingenuity in influencing the direction of technology as we continue to push the boundaries of what is possible.

Reference II - Quantum Dots Displays

Quantum Dot (QD)-based Micro-LED displays have become a shining example of innovation in the rapidly evolving field of display technology, offering brighter colors and higher efficiency. However, how precisely are these artistic marvels created? Together, we will explore the painstaking fabrication process that results in the realization of QD-based Micro-LED displays.

LED epitaxy and chip processing are the first steps in the process, and they are vital since they create the groundwork for the display. Picture a canvas that is ready to be painted. Metal-organic chemical vapor deposition (MOCVD) is the technique used to develop layers of gallium nitride (GaN) and indium nitride (InGaN). The substrate is prepared. These strata act as the foundation for the display's brilliant appearance.

But that's only the start. Now for the exciting part: a range of hues can be unlocked with the help of microscopic semiconductor particles called Quantum Dots. The real magic is in the color conversion using quantum dots (QDs). These little marvels have three key qualities that make them invaluable in the field of display technology: narrow emission linewidths, excellent photoluminescence quantum yields, and solution processing capability.

Imagine a symphony of color and light right now. A vital component of the LED's toolkit, the blue excitation light needs to be carefully controlled to guarantee the best possible color purity. This is where display engineering artistry becomes useful. Similar methods are used, such as using Quantum Dots themselves to absorb blue light or a distributed Bragg reflector (DBR) structure.
What was the outcome? A QD-based Micro-LED display that emanates brightness, clarity, and depth like never before is a visual feast that captivates the senses. But beneath this show is a symphony of inventive engineering and painstaking craftsmanship, with every move being expertly timed to perfection.

Even as we marvel at the amazing images that QD-based Micro-LED displays bring to life, we also need to acknowledge the complex process that goes into making them. Every step of the production process, from blue excitation light management to QD color conversion and LED epitaxy, is crucial in creating the finished item.

However, the tale is not over yet. Every advancement in display technology creates new opportunities and experiences, and this process of evolution is never-ending. As we learn more about QD-based Micro-LED displays, we see a bright future where visual storytelling soars to previously unheard-of heights and captivates people's hearts and minds with its radiant appeal.

In conclusion, the process used to fabricate QD-based Micro-LED displays is proof of the inventiveness and resourcefulness of humankind. Every step of the way, from the dexterity of blue excitation light control to the revolutionary potential of quantum dots and LED epitaxy, demonstrates a commitment to pushing the envelope of display technology.

Conclusion & Future Scope

Micro-LED displays have a bright future ahead of them thanks to the technologies covered in this article, which establish them as leaders in the field of display technology. Micro-LEDs have several benefits, including low power consumption, long lifespan, fast response times, and wide color range. These advantages could completely change how humans interact with visual content.The future of micro-LEDs is bright, despite obstacles including efficiency deterioration and expensive production. These issues are being overcome by further research and development. Micro-LEDs will be successfully integrated into next-generation smart display goods thanks to strategies that aim to increase light extraction efficiency, refine color conversion technologies using quantum dots and nanoparticles, and investigate novel mass transfer techniques.Future technological developments point to a more promising future for the use of micro-LEDs in display technology. We expect to see the introduction of high-resolution, eco-friendly, and energy-efficient smart display solutions that take advantage of micro-LED technology's extraordinary potential as developments continue.

In summary, it will take tenacity, creativity, and an unwavering quest of perfection to fully realize the potential of micro-LED displays. We are getting closer to a time when micro-LEDs will rule the day, revolutionizing how we consume visual media and expanding the potential of display technology.

References

- Main paper - Recent processes in Micro-LED based Display technologies (https://onlinelibrary.wiley.com/doi/epdf/10.1002/lpor.202100427)

- Reference I - Tripling the Optical Efficiency of Color-Converted Micro-LED Displays with Funnel-Tube Array ([170] - F. Gou, E.-L. Hsiang, G. Tan, Y.-F. Lan, C.-Y. Tsai, S.-T. Wu,Crystals2019,9, 39.) (https://www.mdpi.com/2073-4352/9/1/39)

- Reference II - Micro-light-emitting diodes with quantum dots in display technology([23]Z. Liu, C.-H. Lin, B.-R. Hyun, C.-W. Sher, Z. Lv, B. Luo, F. Jiang, T.Wu, C.-H. Ho, H.-C. Kuo, J.-H. He,Light: Sci. Appl.2020,9, 83.) (https://www.nature.com/articles/s41377-020-0268-1)

- Image source: Google images