Proceedings of the 2023 International Conference on Functional Materials and Civil Engineering
DOI: 10.54254/2755-2721/25/20230767

Recent research on the status and advances of OLED

Jialin Zhang

Shrewsbury School, Shrewsbury, SY3 7BA, United Kingdom

SCG@shrewsbury.org.uk

Abstract. Organic Light-Emitting Diodes (OLEDs) have already been a prominent display technology in various applications for many decades, ranging from smartphones and televisions to wearable devices and lighting. It is important to understand the current state of OLED research in order to assess its progress, identify challenges, and explore more potential ways for further development. In this paper, the significance and widespread adoption of OLED technology are briefly introduced, and its advantages over traditional display technologies are highlighted. The paper then provides a concise overview of the major components and working principles of OLEDs without delving into basic notions. The paper discusses both small molecule OLEDs (SMOLEDs) and polymer OLEDs (POLEDs), emphasizing their unique structure, characteristics and properties. Different strategies employed to enhance OLED performance is investigated, including the regulation of band gaps that influence the efficiency and brightness. This paper also focuses on the evaluation of device reliability and stability aspects. The techniques and materials employed in studies related to OLED development are also discussed with many searched experimental data and ongoing research activities. Furthermore, the research content covered the aspects of recent commercial advancements in OLED technology, such as Active matrix OLEDs (AMOLED) and Passive matrix (PMOLED). The review provides a guideline for researchers, industry professionals, and enthusiasts to better understand the OLED technology into its details, potential, and the areas that require further exploration.

Keywords: OLED, light-emitting layer, charge transport layer, electrode.

1. Introduction

In display technologies, the invention of OLED is marked by continuous innovations and breakthroughs. From the bulky CRT monitors to the smooth LCD and LED screens, each step has brought people closer to a fascinating visual experience. However, the emergence of Organic Light-Emitting Diode (OLED) technology has truly revolutionized the world of displays.

The transition from CRT to LCD to LED acted as a significant milestone, reducing the size and improving the image quality of displays. However, introducing OLED technology brought a fresh experience to the public. OLED is a display technology that utilizes thin, organic materials to emit light when an electric current is applied. Unlike its predecessors, OLED displays can self-illuminate, offering vibrant colors, exceptional contrast ratios, and perfect black levels. This distinctive feature eliminates the need for backlighting, resulting in thinner and more flexible screens.

With technological advancement, OLED comes with its advantages and disadvantages. On the positive side, OLED displays provide a wider viewing angle, faster response times, and superior color reproduction compared to LCD or LED. Additionally, OLEDs consume less power when displaying dark or black content, contributing to energy efficiency. However, OLED displays are more susceptible to burn-in, where the prolonged collection of static images can cause image retention. Furthermore, OLED panels have a shorter lifespan than LCD, as the organic materials degrade over time.

The applications of OLED extend across various industries, ranging from consumer electronics to automotive and lighting. OLED screens could fit into smartphones, tablets, televisions, and computer monitors, delivering stunning visuals and enhancing the user experience. In the automotive sector, OLED displays are utilized in dashboard instrument clusters and infotainment systems, providing clear and dynamic information to drivers. Additionally, OLED technology has paved the way for innovative lighting solutions, including flexible and transparent panels that offer new possibilities in interior design and architectural lighting.

To comprehend the inner working principles of OLED, it is essential to understand its structure and the production methods employed. OLED displays consist of multiple layers of organic materials sandwiched between a cathode and an anode. These organic layers include emissive and conductive materials and charge transport layers. Various production techniques, such as roll-to-roll, vapor deposition and solution processing, are adopted to create these layers and assemble the OLED devices. These production methods determine OLED displays' performance and image quality.

In this paper, the details of the structures of typical OLEDs will be introduced, including the anodes and cathodes on the outer side, the two essential charge transport layers for an OLED to operate and the core of the OLED that ultimately emit the desired type of light.

2. Electrodes

The anode and cathode components play vital roles in the operation of OLED displays. Materials such as ITO, graphene, aluminum, calcium, and barium are commonly used in these components due to their electrical properties and compatibility with organic materials.

2.1. Anode materials

The anode in an OLED serves as the anode, injecting holes into the organic layer to initiate light emission. Indium Tin Oxide (ITO) is a widely used anode material due to its high transparency, high conductivity and, particularly, high work function [1]. ITO-coated glass substrates offer excellent light transmission properties, ensuring minimal interference with the emitted light.

Graphene is another commonly employed anode material, a single layer of carbon atoms arranged in a two-dimensional lattice. Graphene offers high electrical conductivity, high luminous efficiencies and transparency, making it a promising candidate for future OLED applications [2]. Its exceptional mechanical strength and flexibility make it suitable for flexible OLED displays.

2.2. Cathode materials

The cathode acts as the cathode in an OLED, injecting electrons into the organic layer to complete the light-emitting process. One prevalent cathode material is Aluminum (Al). It possesses excellent electron injection characteristics and good compatibility with organic materials. Co-deposition of the cathode with 96% Al and 4% Silver (Ag) shows transmittance at 520 nm (T@520nm) of 83.5% and sheet resistance as low as 7.0 Ω/□ with nearly no particular mixing of Ag:Al (4%, 14 nm) is noticed by the thermal annealing of the fabricated cathode at 85 °C, 240 h for transparent OLEDs (TOLEDs) applications. The fabricated TOLED with this Ag:Al (4%, 14 nm) cathode shows an outstanding electron injection property with a T@520nm of 83.5%, and achieved current efficiencies of 36 and 18 cd/A from the bottom and top sides emissions, respectively [3].

Calcium (Ca) and barium (Ba) are also frequently used as cathode materials. They offer low work functions, facilitating efficient electron injection. However, these materials require the addition of a protective layer to prevent degradation and enhance the device’s lifetime as these metals are highly reactive and unstable in air.

DOI: 10.54254/2755-2721/25/20230767

In addition to the materials used, OLEDs can be categorized into different types based on their cathode and anode configurations. Here are a few common styles:

1. Top-Emitting OLED: This configuration features a transparent anode (e.g., ITO) placed on top of the OLED stack, allowing emitted light to pass through the anode and the substrate.

2. Bottom-Emitting OLED: In this configuration, the anode is placed beneath the OLED stack, and the emitted light exits through the substrate. The choice of materials for the anode depends on the transparency requirements and specific device design.

3. Stacked OLED: Stacked OLEDs consist of multiple layers of OLED stacked on top of each other. Each layer can have its own anode and cathode, allowing for complex color combinations and improved color accuracy.

3. Charge transport layer

The Hole Transport Layer (HTL) and Electron Transport Layer (ETL) are integral components of OLED technology. Various organic materials are used including inorganic substances and organic macromolecules and simple molecules.

The selection of appropriate HTL and ETL materials is essential for achieving efficient charge transport, balanced recombination, and optimal device performance. Extensive research and development efforts continue to explore new materials, pushing the boundaries of OLED technology and paving the way for improved efficiency, longevity, and visual quality.

3.1. Hole transport layer (HTL)

The HTL is a fundamental component of OLED devices, positioned between the anode and the emissive layer. By efficiently transporting holes, the HTL ensures a balanced charge distribution within the device. This balance is crucial for the optimal recombination of holes and electrons in the light-emitting layer, resulting in the desired light emission. Moreover, the HTL also assists in hole injection from the anode into the organic layers, minimizing energy losses and enhancing device efficiency.

Several materials have been developed and employed as HTLs, each possessing unique properties that make them suitable for specific applications. Here, some commonly used HTL materials and their relevant properties are introduced.

N,N’-Bis(3-methylphenyl)-N,N’-diphenylbenzidine (TPD) is a widely utilized HTL material for its high hole-transporting ability (its hole mobility is 1×10^{-2} cm^2V^$^{-1}s^{-1}$) and relatively convenient synthesis routes [4]. Its exceptional film-forming properties, favorable energy level alignment, good film-forming properties, and compatibility with various device architectures, good charge transport characteristics, and compatibility with other organic layers make it a popular choice in OLED devices. TPD has been extensively studied and employed in various commercial OLED displays, ensuring efficient hole injection and transport. Poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) is a conductive polymer blend frequently used as an HTL. Even though PEDOT polymer is insoluble, it becomes more soluble after polymerizing EDOT that is combined with a water dispersible polyelectrolyte such as polystyrene sulfonic acid (PSS) [5]. It offers excellent hole conductivity, transparency, and film-forming capabilities. PEDOT:PSS exhibits good compatibility with other layers in the OLED stack and has been widely employed in flexible OLED displays due to its mechanical flexibility and robust performance.

3.2. Functions and definitions of the electron transport layer (ETL)

The ETL is another critical component between the OLED devices’ cathode and an EML. The primary function of the ETL is to facilitate the efficient transport of negative charge carriers, known as electrons, from the cathode toward the EML.

The ETL promotes the balanced distribution of electrons within the OLED structure, ensuring their timely arrival at the EML. For hole recombination. Efficient electron transport is crucial for achieving

DOI: 10.54254/2755-2721/25/20230767

high device performance and minimizing energy losses. Additionally, the ETL assists in electron injection from the cathode, enhancing overall device efficiency.

3.2.1. Commonly used materials for the electron transporting layer (ETL). Various materials have been developed and employed as ETLs in OLED devices. These materials exhibit favorable electron transport properties, compatibility with other layers, and suitable energy level alignment. Here are two commonly used ETL materials:

Tris(8-hydroxyquinolinato) aluminum (Alq_3) is a well-known ETL material widely recognized for its high electron mobility and efficient electron-transporting properties. It exhibits a solid capability to transport and inject electrons into the EML, contributing to overall device performance. Alq3's stability, compatibility with other organic layers, and good film-forming characteristics have made it a popular choice in OLED technology. In addition, Bathocuproine (BCP) is a commonly employed hole-blocking material between the EML and the anode to prevent electrons from leaking into the HTL. BCP enhances the overall device efficiency and reduces leakage currents and thus prevents degradation of OLED devices. Its compatibility with various organic materials and suitable energy level alignment make it desirable for achieving high-performance OLEDs.

3.2.2. HOMO/LUMO band gap regulation for efficient electron transport in ETL. The band gap between the HOMO and LUMO levels significantly influences the electron transport properties within the ETL of an OLED. By regulating this band gap, several advantages can be achieved, including improved charge injection, reduced energy losses, and enhanced device efficiency. Here are some methods employed to fine-tune the band gap for efficient electron transport:

Molecular Engineering:

Molecular engineering involves modifying the molecular structure of materials used in the ETL to adjust their energy levels and bandgap. The HOMO and LUMO levels can be effectively tuned by introducing specific functional groups or substituents. This approach allows for the precise control of energy level alignment, ensuring efficient electron injection and transport within the ETL.

Doping Techniques:

Doping refers to the introduction of dopant molecules into the ETL material matrix. This technique enables manipulating the energy levels and band gap by altering the charge distribution and carrier concentration. Doping can be performed through either molecular doping or host-guest doping, where dopant molecules are incorporated either within the ETL material or as separate guest molecules. Proper selection and optimization of dopants can lead to improved electron transport properties and enhanced device performance.

Exciton Engineering:

Excitons are the bound electron-hole pairs formed during electron and hole recombination within the EML, and play a crucial role in OLED operation. Exciton engineering techniques focus on modifying the exciton formation and dissociation processes, ultimately influencing the energy transfer efficiency and reducing exciton quenching. By carefully designing the ETL materials and their interfaces, exciton diffusion and dissociation can be optimized, improving electron transport and overall device efficiency.

Interface Engineering:

Interface engineering involves the modification of the interfaces between different layers within the OLED structure, including the ETL. By introducing interfacial layers or interlayers, the energy level alignment and charge carrier injection can be finely tuned. This approach ensures efficient electron injection into the ETL from the adjacent layer, minimizes energy losses at the interfaces, and facilitates smooth electron transport within the ETL.

4. Light emitting layer (EML)

The EML plays a pivotal role in the luminous charm of OLED technology. It enables the recombination of charge carriers to release photons, producing vibrant light emissions. Optimal brightness, color accuracy, and device efficiency can be achieved by carefully selecting organic materials such as small molecules or polymers for the EML.

The continuous exploration and development of new EML materials contribute to the advancement of OLED technology, propelling displays toward increased efficiency, longevity, and visual appeal. Integrating diverse materials within the EML broadens the possibilities for applications ranging from televisions and smartphones to lighting solutions, captivating viewers with their brilliant and dynamic displays.

The EML represents the heart of an OLED, situated between the HTL and the ETL. As the name suggests, the EML is responsible for emitting light when an electric current is applied.

The primary function of the EML is to facilitate the recombination of charge carriers, specifically the holes and electrons transported from the HTL and ETL, respectively. As the holes and electrons meet within the EML, their recombination releases energy in the form of photons, resulting in the desired light emission. The efficiency and quality of the EML play a pivotal role in determining the brightness, color accuracy, and overall visual performance of an OLED display.

4.1. Commonly used materials for the EMLs

A diverse range of organic materials has been developed and utilized in constructing the EML, each with distinct properties that make them suitable for different applications.

4.1.1. Small molecule-based EMLs. Alq_3 is a classic small molecule-based material widely employed in EMLs and emits bright green-colored light after exposure and being excited under UV radiation or light [6]. It has exceptional electroluminescent properties, providing high external quantum efficiency (EQE) in Alq3-based OLEDs peaking at about 4.6% and a broad fluorescence emission band peaking at around 478 nm in the methanol and ethanol (ME) matrix at 77 K [6,7]. After the measuring of a phosphoroscope, the emission spectrum has two emission bands at 567 nm and 478 nm [6]. Its stable molecular structure and convenience of synthesis contribute to its popularity in achieving green and shifting to red emissions by synthesizing its derivatives.

(2,2',2''-(1,3,5-benzinetriyl)-tris(1-phenyl-1-H-benzimidazole)) (DPVBi) is another small molecule frequently used in EMLs. It demonstrates efficient blue emission and possesses favorable film-forming properties. DPVBi's stability and compatibility with other organic layers have positioned it as a valuable material for realizing high-performance blue OLEDs as it could effectively manipulate the energy barrier between the ITO and EML. Therefore, the hole injection property is significantly enhanced. The current density and luminescence of standard OLED devices—ITO/DPVBi/NPB/Alq_3/LiF/Al—were significantly enhanced as a result of inserting a few nanometer-DPVBi as a hole injection layer. Under the optimum thickness of DPVBi HIL (3 nm), the operating voltage (voltage at 1,000 cd/m^2 luminescence) of standard OLED devices decreased down to 4.9 V and the device lifetime was also remarkably enhanced [8].

4.1.2. Thermally activated delayed fluorescence (TADF)-based EMLs. 4CzIPN (4,4'-bis(carbazol-9-yl)biphenyl) has a unique molecular structure that promotes an efficient reverse intersystem crossing (RISC) process, which allows it to effectively convert triplet excitons into radiative singlet excitons and avoiding the waste of energy by going through intersystem crossing (ISC) that is non-emissive and wastes energy. OLEDs employing 4CzIPN as the EML have shown high device efficiencies and reduced efficiency roll-off. A high record of EQE of nearly 32.2% in a blue OLED was produced with 4CzIPN as the EML [9,10]. The principles of TADF materials are similar since they all have the ability to undergo the RISC process, such as AcA (2-phenyl-4-(1,3-diphenyl-1H-pyrazol-4-yl)pyridine), which is also a TADF material.

4.2. Rationale for material selection

The selection of materials for the EML involves careful consideration of several factors, including electroluminescent efficiency, stability, compatibility with other layers, and tunability of emission wavelengths. Materials exhibiting high quantum efficiency, good film-forming properties, and thermal stability are preferred to achieve optimal light output and ensure long-term device reliability.

The choice of materials also considers the desired emission color by selecting specific organic molecules or polymers. A wide range of emission wavelengths can be achieved, from deep red to green and blue. This development of materials with broad color ranges enables the realization of full-color OLED displays.

Furthermore, materials that can be easily processed through solution-based techniques, such as spin-coating or inkjet printing, offer cost-effective and scalable manufacturing options. Compatibility with flexible substrates further enables the production of bendable and rollable OLED devices, expanding their applications to flexible displays and lighting solutions.

5. Recent advanced technology for commercial use

OLED technology has experienced remarkable advancements in recent years, propelling its widespread adoption in diverse commercial applications. This section explores the current developments in OLED technology, focusing on the active and passive matrix configurations. This part will probe into their benefits, applications, and the impact these advancements have had on industries such as displays, lighting, and wearable devices.

5.1. Active matrix OLED (AMOLED)

AMOLED displays have emerged as a leading technology in the consumer electronics market, revolutionizing how people interact with exhibits. Unlike their passive matrix counterparts, AMOLED displays utilize a thin-film transistor (TFT) array, enabling each OLED pixel to be individually controlled. This configuration offers several following advantages.

5.1.1. Wide viewing angles. AMOLED displays offer wider viewing angles compared to other display technologies like LCD due to the individual pixel control enabled by TFT array. The ability to control the brightness and color of each pixel independently ensures consistent image quality even when viewed from different angles, enhancing the overall viewing experience.

5.1.2. Superior image quality. AMOLED displays deliver exceptional image quality, with high contrast ratios, wide color gamut, and deep blacks. Each pixel's individual control allows for precise brightness and color adjustments, resulting in vivid and immersive visual experiences [11]. AMOLED displays are ideal for high-resolution applications such as smartphones, tablets, and televisions.

5.1.3. More design possibilities. The flexibility of AMOLED technology allows for the creation of curved and flexible displays. This versatility has revolutionized product designs, enabling innovative form factors such as curved smartphones, wrap-around displays, and flexible wearables. AMOLED displays provide an immersive viewing experience and captivate consumers with sleek and futuristic designs.

5.1.4. Energy efficiency. AMOLED displays consume less power compared to traditional LCDs. As each pixel emits light individually, there is no need for a backlight, resulting in energy savings and improved battery life in portable devices. Energy-efficient AMOLED displays have become crucial in addressing the increasing demand for longer-lasting devices.

5.2. Passive matrix OLED (PMOLED)

While AMOLED dominates the high-end display market, PMOLED technology remains relevant in specific applications. PMOLED displays employ a simpler driving scheme, with row and column electrodes controlling the OLED pixels. Although PMOLED has some limitations compared to AMOLED, it offers distinct advantages.

5.2.1. Cost-effectiveness. PMOLED displays are relatively cost-effective to manufacture, making them suitable for applications where cost is a primary consideration. They find application in small-sized displays, such as wearable devices, automotive displays, and industrial equipment interfaces. The low manufacturing complexity and low power consumption of PMOLED contribute to its affordability [12].

5.2.2. Commercial application use. PMOLED displays are well-suited for applications where size and simplicity are paramount. They find applications in appliances, home automation systems, and small-scale information displays. Their ease of integration and compatibility with various devices make them a practical choice in these contexts.

6. Conclusion

In summary, the typical materials of anodes and cathodes are described and OLED is further categorized into different types according to the configurations of the electrodes. The functions and definitions of HTL, ETL and EML are stated and details along with properties of commonly employed materials are introduced. In addition, the rationale for the material selection of EML is explained. Finally, recent commercial progressive technological types of OLEDs, AMOLED and PMOLED, are introduced and benefits that enable them to be suitable for mass production are discussed.

While OLED technology offers numerous advantages, including self-emissive properties, thinner screens, wider viewing angles, faster response times, and superior color reproduction, it also has limitations that need to be addressed. Burn-in issues and the limited lifespan of OLED panels remain challenges that require further research and development efforts.

Looking ahead, the prospects for OLED technology are promising. Continuous advancements in materials, manufacturing techniques, and engineering approaches are expected to overcome the current limitations. Efforts to improve durability, reduce burn-in risks, and extend the lifespan of OLED displays are already underway.

Additionally, OLED technology will likely find new applications and expand its presence in various industries. Consumer electronics, automotive, and lighting sectors will continue to benefit from OLED displays' captivating visual experiences and energy-efficient characteristics. The flexibility and versatility of OLED technology may lead to its fusion into unconventional devices and applications, further diversifying our daily lives.

Moreover, future developments may include advancements in transparent OLED displays, foldable and rollable screens, and increased efficiency through the use of novel materials and manufacturing processes. As OLED technology continues to evolve, we can anticipate even more stunning displays, innovative designs, and improved performance to appear soon.

References

[1] Chan IM, Franklin C. Hong, 2004 *Thin Solid Films* 450 304-311
[2] Han, TH., Lee, Y., Choi, MR. *et al.* 2012 *Nature Photon* 6 105–110
[3] Song M G, Kim K S, Yang H I, et al. *Organic Electronics* 76 105418
[4] Deng J, Xie G, Yu J, et al., 2007 "Study on the performance of organic light-emitting diode with N,N'-bis(3-methylphenyl)-N,N'-diphenylbenzidine doped in polystyrene as hole transporting layer," Proc. SPIE 6722, 3rd International Symposium on Advanced Optical Manufacturing and Testing Technologies: Advanced Optical Manufacturing Technologies (SPIE: Chengdu) p.67223P
[5] Petrosino, M., Vacca, P., Miscioscia, R., et al. 2007 Effect of PEDOT: PSS ratio on the electrical and optical properties of OLEDs. In *Photonic Materials, Devices, and Applications II* (SPIE: Maspalomas, Gran Canaria) p. 279-28
[6] Hoshi T, Kumagai K, Inoue K, et al., 2008 *Journal of Luminescenc* 128 1353-1358
[7] Pérez-Bolívar, C., Takizawa, S.-y., Nishimura, G., et al. 2011 *Chem. Eur. J.* 17 9076-9082

[8] Yun, W. M., Park, C. E., & Chung, D. S. 2013 *Journal of nanoscience and nanotechnology* 13 2166–2170
[9] Chen, C.-H., Ding, W.-C., Lin, B.-Y., et al. 2021 *Adv. Optical Mater.* 9 2100857
[10] Wang P, Zhao S, Xu Z, et al. 2016 *Molecules* 21 1365
[11] Pang H, Rajan K, Silvernail J, et al., 2011 "Recent progress of flexible AMOLED displays," Proc. SPIE 7956, Advances in Display Technologies; and E-papers and Flexible Displays, (SPIE: San Francisco, CA) p. 79560J
[12] Keramatikerman M, 2020 *International Journal of Engineering Applied Sciences and Technology* 4 587-591