Recent Advances and Future Trends in Flexible OLED Encapsulation Technology

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Abstract. Organic Light Emitting Diode (OLED) technology is a rapidly advancing display technology widely used in consumer electronics due to its self-emissive nature, vibrant colour output, and ultra-thin form factor. However, the reliability and lifespan of OLED devices remain critical concerns, especially under environmental stresses such as moisture, oxygen, temperature, and mechanical deformation. Encapsulation technology plays a vital role in protecting OLEDs from degradation, directly influencing device durability and performance. This paper offers an in-depth overview of the underlying physical mechanisms and recent innovations in OLED encapsulation technology, with a particular focus on flexible and high-performance encapsulation approaches. It outlines several major challenges, such as the limited effectiveness of single-layer inorganic barriers, the inherent brittleness of many barrier materials, stress accumulation within multilayer structures, and the demand for improved mechanical durability in flexible devices. The review emphasizes advancements in multilayer encapsulation systems, neutral-axis design strategies, and the application of nanotechnology to improve both gas barrier properties and mechanical robustness. In addition, it explores the adoption of advanced thin-film deposition methods—specifically Atomic Layer Deposition (ALD) and Molecular Layer Deposition (MLD)—to fabricate ultrathin encapsulation layers that offer low water vapor transmission rates (WVTR) and high structural reliability. The combination of organic–inorganic hybrid materials and stress redistribution through neutral axis positioning is also presented as a promising direction for reducing stress-induced failures in flexible OLED applications.

INTRODUCTION

Organic light-emitting diode (OLED) is an advanced display technology. Each pixel can emit light on its own without the need for backlight mode, which makes the screen thinner, with higher contrast and brightness. It is widely used in electronic devices such as smartphones and televisions. Although OLED technology has recently made significant progress, the problem of lifespan has been a huge challenge for many years.

The principle of OLEDs is based on the electroluminescence of organic molecules. When voltage is applied across the layers, electrons and holes recombine in the emissive layer and generate photons. Due to the organic nature of the materials, these layers are highly susceptible to ambient oxygen and moisture. This phenomenon degrades the light-emitting efficiency and structural integrity.

Many factors can affect the lifespan of OLEDs. Among them, moisture, oxygen, heat, electric fields, and light are the main causes of degradation in organic light-emitting devices. In particular, corrosion triggered by water and oxygen is the most significant, as it shortens the device's lifespan by creating or enlarging dark spots, altering the structure of the organic electronic layers, and chemically corroding the cathode [1,2].

The encapsulation technology of the OLED can diminish the environmental influences of the OLED lifespan. Despite significant research progress in this field, the technology still encounters numerous unsolved issues in real-world implementation. The following are the major technological challenges:

(1) Single-layer inorganic films (Al_2O_3, SiO_2, TiO_2) can hamper the moisture and their effectiveness is limited due to microcracks and pinhole defects [3]. In order to improve the barrier performance, the conventional approach is increased film thickness, but this approach will affect the issues of Mechanical stress and fragility [4].

(2) With the requirements of the new types of displays such as foldable and wearable ones, the encapsulation layer must possess flexibility which makes the traditional rigid materials become unsuitable [5].

(3) Some inorganic materials (such as Al_2O_3) exhibit excellent barrier properties, but they are brittle and prone to cracking. In the high-temperature and humid conditions, inorganic materials performance deteriorates rapidly [4,5].

(4) The multi-layer structures are prone to internal stresses between layers, which will jeopardize the film warping or cracking. Nano-defects, likes pinholes, are also difficult to completely avoid during the film deposition process [3].

These issues significantly restrict the application of the OLED technology in both daily life and harsh environment. In order to advance OLED encapsulation technology, a systematic review and deep analysis of the aforementioned problems are still required.

The author provides a systematic review of the physical mechanisms and structural innovation pathways in OLED encapsulation technology, focusing on the key issues of the water vapor permeation in high-humidity environments, bending and cracking of encapsulation layers, and defect diffusion paths leading to encapsulation failure. The paper also introduces new flexible encapsulation technologies utilizing nanotechnology and multi-layer encapsulation structures. Looking ahead, OLED encapsulation technology is expected to evolve towards fully flexible, multifunctional integration, and green manufacturing, providing crucial support for the commercialization of flexible electronics and wearable devices.

INTRODUCTION TO OLED DEVICE ENCAPSULATION TECHNOLOGY

The OLED encapsulation technology is a critical process which apply to protect organic light-emitting diode device from environmental degradation. This technology directly impacts the lifespan and performance of the OLED.

In summary, a qualified encapsulation technology should fulfill the following three key objectives:

(1) It must block the water and oxygen into the device directly;

(2) It must provide the mechanical protection and prevent the leakage of systems such as the perovskite materials leakage;

(3) It must confine the volatile substance within a small, sealed cavity to prevent their escape [6].

In addition to these fundamental roles, encapsulation also contributes to mechanical reinforcement in flexible devices, prevents electrode delamination, and minimizes gas ingress paths in foldable or curved surfaces.

In general, in order to ensure the utility lifespan of OLEDs, it is essential to require the water vapor transmission rate (WVTR) of the device encapsulation is less than 10^{-6} g/(m² • d) and the oxygen transmission rate (OTR) is less than 10^{-5} cm³ /(m² • d) [7].

In recent years, the demand for foldable, wearable and stretchable OLED devices has been steadily increasing, which has promoted the development of flexible OLED encapsulation technology. Flexible encapsulation technology has disparities of the traditional rigid encapsulation methods (as shown in Figure 1). The flexible film encapsulation does not require the materials such as metals, sealants and desiccants. Instead, it uses some high-strength, corrosion-resistant oxides and organic materials. These materials make the OLED more convenient and easier to conform to the substrate.

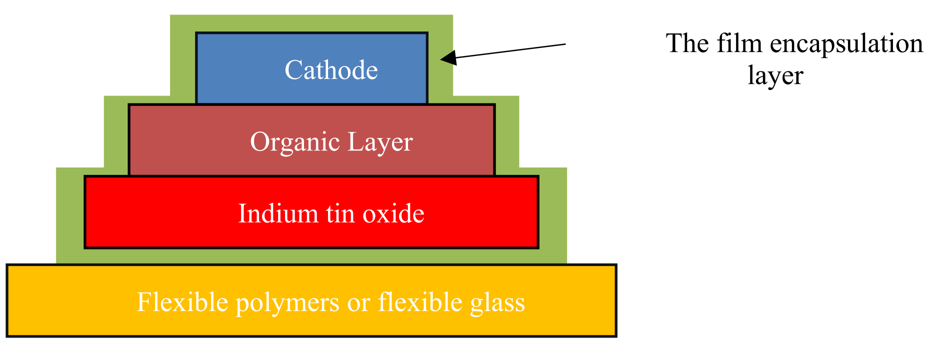
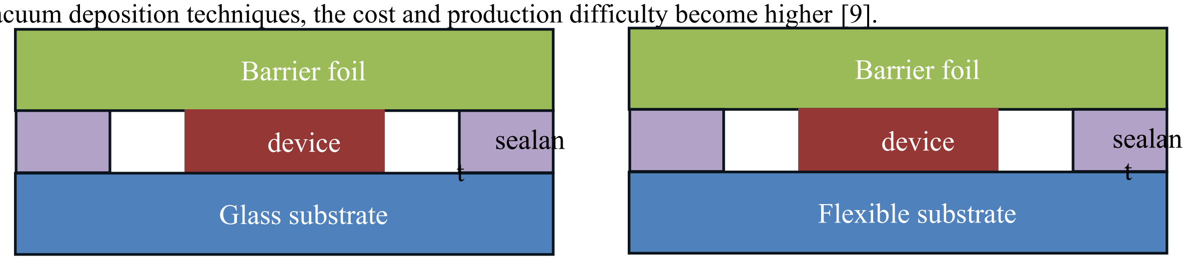


FIGURE 1. Schematic representation of thin-film encapsulation [8]

In the present, the widely used flexible encapsulation technologies can generally be divided into two types: Barrier Foil Encapsulation and Thin-Film Encapsulation.

Barrier foil encapsulation (as shown in Figure 2(a)) uses a layer of water or oxygen-resistant on the OLEDs surface to achieve the encapsulation purpose. This device often laminated onto the OLED and sealed at the edges by sealants after the fabrication, which means this technology has a certain degree of flexibility and is suitable for roll-to-roll production. However, because of the property of sealants, the sealant can degrade due to factors such as temperature, humidity and etc. which lead to internal OLED device corrosion.

Thin-film encapsulation (as shown in Figure 2(b)) uses some high-strength, corrosion- resistant oxides, nitrides and organic materials onto the device surface to form a dense and flexible encapsulation layer which covers the whole device. This means the sealing performance of this technology is superb. However, due to apply some high-precision vacuum deposition techniques, the cost and production difficulty become higher [9].



(a) (b)

FIGURE 2. (a) The structure of the barrier foil encapsulation. (b) The structure of the thin-film encapsulation [9].

THE INNOVATION OF THE ENCAPSULATION TECHNOLOGY OF OLED

Despite there have been posed various encapsulation technology and applied into the protection of OLED devices, these technologies still have limited in the performance. Especially in the reliability, flexibility, mechanical strength. The long-term reliability assurance of the devices in practical application has yet to meet the increasingly demanding technological requirements. Therefore, this field continues to attract a large number of researchers who are eager to explore and innovate the new things, aiming to develop higher-performance encapsulation solutions to resolve the present problems and applies to the next generation of flexible displays.

Multilayer Film Encapsulation Technology

As mentioned in the introduction, single-layer inorganic films have limited barrier capabilities due to material defects. Blindly increasing the thickness of the barrier layer would significantly reduce flexibility. Although organic layers, when used alone, exhibit excellent flexibility and ductility, they fail to meet encapsulation standards due to their high WVTR. Therefore, they are typically combined with inorganic layers (such as Al_2O_3) to achieve better gas barrier performance [3].

The Yun Cheol Han team, based on FEA (Finite Element Analysis), analyzed the mechanical properties of multilayer structures, and established two types of multilayer structures using 3.5 binary moisture barrier materials and FOLEDs encapsulation materials sandwiched between PET substrates and the hybrimer [10]. The multilayer structure of 3.5 binary moisture barrier materials is based on the alternating stacking of three groups of Al_2O_3 and S-H nanocomposites, with an additional layer of alumina deposited on top. This structure effectively compensates for the deterioration of barrier performance caused by defects in the stacking of organic and inorganic layers and prevents defects from occurring in adjacent layers. It effectively addresses the issue of cracking in the encapsulation layer under bending conditions, which would otherwise lead to water vapor infiltration.

At the same time, the Park team proposed a multilayer encapsulation structure formed by alternating 4-mercaptophenol (4MP) organic monolayers and Al_2O_3 inorganic nanolayers, constructed using Molecular Layer Deposition (MLD) and Atomic Layer Deposition (ALD) techniques. This structure has an ultra-low WVTR and maintains excellent barrier performance after 1000 cycles of bending at a 3mm radius [11].

This material effectively addresses the challenge of balancing barrier performance with mechanical flexibility in flexible electronics encapsulation. Building on this, Seo et al. introduced a hybrid multilayer structure composed of alternating organic and inorganic layers (dyads), fabricated through Atomic Layer Deposition (ALD) and Plasma-Enhanced Chemical Vapor Deposition (PECVD). Their design uses a 20 nm-thick Al_2O_3 layer as the inorganic barrier and plasma-polymerized hexane as the organic buffer. The resulting film not only demonstrates ultra-low WVTR but also shows remarkable flexibility. Tests revealed that the encapsulation structure delayed calcium layer oxidation even under repeated bending, confirming its integrity and durability [12].

To further improve reliability, other researchers have explored similar dyad structures using materials like SiNx or TiOx for the inorganic layers, paired with polymeric components such as parylene C or polyimide (PI). These hybrid configurations leverage the "tortuous path" effect, which effectively hinders gas permeation and maintains protection performance during thermal cycling and mechanical deformation [5].

Overall, by layering organic and inorganic materials with tailored thickness and properties, multilayer encapsulation has emerged as a leading solution in flexible OLED protection. It not only extends device lifespan and boosts mechanical performance but also overcomes the long-standing issue of achieving robust water vapor barriers in high-stress applications—establishing it as the mainstream encapsulation strategy in the field.

The Neutral Axis Engineering in Encapsulation Technology

In order to improve the mechanical reliability performance of flexible OLED encapsulation systems, Neutral Axis Engineering (NAE), which locates the weakest link (Al_2O_3) on the NA (the location with 0 strain when bending occurs) by adjusting the thicknesses and elastic moduli of all layers, was proposed recently. In NAE scheme, the failure mechanism changes from direct fracture of Al_2O_3 layer into fatigue cracks initiated from weak points such as interfaces or defects. So, the probability of crack initiation decreases dramatically since the Al_2O_3 layer is located away from any potential weakness. As a result, more durable devices can be achieved.

Han and colleagues conducted a study on stress concentration phenomena in flexible OLEDs using finite element analysis (FEA). By placing a buffer layer (such as Hybrimer) between the ITO and the encapsulation material—designed with an elastic modulus intermediate between those of the two—they were able to position the Al_2O_3 layer within a region of concentrated stress. Their results showed that a buffer layer with a thickness of approximately 111 μm effectively reduced the degree of stress concentration and allowed the device to maintain performance levels nearly identical to those before bending. [13]

Another approach was proposed by Park and colleagues, who developed an alternating organic–inorganic multilayer encapsulation structure based on the neutral-axis strategy using Molecular Layer Deposition (MLD) . This design combined MLD of 4-mercaptophenol with Atomic Layer Deposition (ALD) of Al_2O_3 to create a multilayer system with exceptionally low water vapor transmission rate (WVTR) and outstanding mechanical flexibility. Under harsh environmental testing conditions (30 °C, 90% relatively humidity), the structure effectively slowed the spread of dark spots caused by moisture ingress, thereby enhancing the environmental stability of OLED devices.[10]

While NAE has proven effective in thin-film encapsulation (TFE) configurations, it alone may not suffice in addressing the broader performance-flexibility trade-offs inherent in more complex multilayer systems. Future research should explore synergistic integration of neutral axis engineering with nanolaminate encapsulation and advanced hybrid barrier designs to develop next-generation flexible OLED encapsulation technologies that offer both superior reliability and mechanical resilience.

Nanotechnology in Encapsulation

With the continued development of OLEDs, higher demands have been placed on the flexibility, size, and airtightness of encapsulation materials. While multilayer encapsulation can effectively address issues such as airtightness, its overall thickness is relatively large, which is not ideal for making ultra-thin and small OLED devices. To address this, researchers have explored the introduction of nanotechnology in encapsulation, utilizing inorganic or organic materials with nanoscale thickness to construct encapsulation layers through precision deposition techniques.

The Hyungjin Lee team proposed a method to infiltrate Al_2O_3 into polyimide (PI) to form a PI – Al_2O_3 hybrid nanolayer. This reduced the water vapor transmission rate (WVTR) from 2.2 g/m^2 • day for bare PI to 1.4×10^{-5} g/m^2 • day. After UV aging, the outgassing decreased by 96%, and under a 0.5mm bending radius, the performance exceeded that of inorganic layers, making it suitable for foldable OLEDs [14]. The Oh team proposed a nanolayer encapsulation structure composed of Al_2O_3 and TiO_2, which can be constructed using thermal ALD at 40° C. The bending strain increased to 0.53%, achieving compatibility between high flexibility and ultra-low water vapor transmission rate [12]. The Wen-Li Chiang team introduced a 1.5 dyads structure composed of $ZnO/Al_2O_3/MgO$ nanometals, which further improved the thermal stability and barrier capabilities of the encapsulation.

Moreover, nano-encapsulation enables sub-50 nm total encapsulation thickness, which is essential for ultrathin flexible displays used in AR/VR applications. These thin layers also show potential in stretchable electronics, where conformability and durability under strain are equally important.

Although nanotechnology in encapsulation shows great potential in performance, challenges remain in large-scale manufacturing, interface engineering, and cost control. Future research can focus on the development of stretchable organic nanolayers, low-temperature high-speed deposition technologies, and roll-to-roll nanofabrication equipment to push this technology toward industrialization.

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CHALLENGES AND DEVELOPMENT TRENDS IN OLED ENCAPSULATION TECHNOLOGY

In the field of OLED encapsulation technology, significant progress has been made, with continuous improvements in the flexibility, sealing, and mechanical strength of encapsulation layers, leading to remarkable achievements. However, as an emerging technology, there are still numerous challenges and limitations.

Although the current inorganic-organic multilayer encapsulation layers exhibit potential in flexibility and sealing performance compared to traditional OLED encapsulation technologies, organic materials still face issues such as poor moisture barrier properties and thermal stability. These problems are critical to the success of OLEDs. To date, many materials and fabrication processes have been explored to reduce manufacturing costs, increase production yields, and enhance the functionality of electronic components, but none have fully achieved these objectives [15].

Additionally, the rapid development of encapsulation technology, from rigid to flexible electronics, has introduced compatibility issues with traditional material structures, especially in ensuring that OLED devices remain operational under pressure and deformation in flexible encapsulations. This is still an important research direction.

In order to address material limitations, research in recent years has increasingly focused on developing self-healing encapsulation films as an innovative solution to improve the mechanical reliability of flexible OLED devices. These encapsulation films are specifically designed to repair microcracks or defects that occur during mechanical deformation processes such as repeated bending, stretching, or folding. Usually, self-healing function is achieved by introducing dynamic covalent bonds, hydrogen bonding networks, or microcapsule healing agents into the packaging matrix, allowing the material to automatically restore its structural integrity after damage [3].

This method not only improves the long-term stability of the barrier by maintaining its barrier properties against moisture and oxygen for a long time, but also helps to maintain optical transparency and mechanical flexibility, both of those are important for next-generation display applications [3]. In addition, self-healing materials can reduce maintenance requirements and equipment failure rates, providing a more sustainable development path for the large-scale commercial application of flexible optoelectronic devices.

Looking ahead to the future, integrating self-healing mechanisms into organic-inorganic hybrid multilayer packaging structures is expected to achieve a balance between ultra-thin device shape and high mechanical toughness, thereby promoting key advances in flexible electronic technology [3].

Looking toward the future, as flexible displays are currently a growing trend, we should continue exploring inorganic-organic hybrid materials and develop new production technologies for large-scale manufacturing. Focusing on controlling the internal stress of OLED encapsulation layers is critical for improving flexibility and mechanical performance in wearable applications. At the same time, the sealing and mechanical strength of encapsulation technologies should also be emphasized, particularly in extreme environments with high temperature, pressure, oxygen, and humidity, where encapsulation should withstand long-term corrosive degradation. This will broaden the application range of OLED technology.

CONCLUSION

OLED encapsulation technology plays a decisive role in extending device lifespan and improving stability, especially in addressing challenges posed by environmental factors such as water vapor and oxygen infiltration, mechanical stress, and thermal stability. In recent years, emerging organic-inorganic multilayer structures and nanotechnology encapsulation have made significant breakthroughs in OLED encapsulation technology. However, key bottlenecks such as material performance limitations, balancing flexibility and barrier properties, and high process costs remain to be addressed.

Future research should focus on developing hybrid encapsulation systems that complement the advantages of different materials, tackling technical bottlenecks, and finding the optimal balance between performance, flexibility, and cost. Meanwhile, enhancing industry-oriented process technology development and internal stress control methods will further improve the manufacturability and long-term reliability of encapsulation technologies. Achieving these goals will effectively promote the broader commercialization of OLED flexible displays and wearable devices. Moreover, with the emergence of skin-conformal devices and biodegradable electronics, encapsulation materials are increasingly required to exhibit both biocompatibility and environmental degradability. Future research should also focus on the development of green synthesis methods and bio-safe polymers to address the dual challenges of regulatory compliance and sustainability goals.

REFERENCES

1. L. S. Liao and C. W. Tang, *Journal of Applied Physics* **104**(4), 594003 (2008).
2. S. F. Lim, W. Wang and S. J. Chua, *Materials Science and Engineering*: B **85**(2-3), 154-159 (2001).
3. Y. Jeon, H. Lee, H. Kim and J.-H. Kwon, *Micromachines* **13**(1478), 594003 (2022).
4. S. J. Oh, S.-W. Lee, T.-S. Kim and J. H. Kwon, *Advanced Materials Technologies* 2024, 594003 (2024).
5. S. W. Lee, Y. H. Son, S. Lee et al., *Advanced Functional Material*s **35**(10), 2411802 (2025).
6. Q. Lu, Z. Yang, X. Meng et al., *Advanced Functional Materials* **31**(23), 2100151 (2021).
7. S. Amberg-Schwab, U. Weber, A. Burger et al., *Monatshefte für Chemie/Chemical Monthly* 137, 657-666 (2006).
8. J. Zhang, G. Zhang, R. Sun et al., *Integration Technology* **3**(6), 92-101 (2014).
9. E. G. Jeong, J. H. Kwon, K. S. Kang et al., *Journal of Information Display* **2**1(1), 19-32 (2020).
10. Y. C. Han, E. G. Jeong, H. Kim et al., *RSC Advances* **6**(47), 40835-40843 (2016).
11. J. Park, J. Seth, S. Cho et al., *Applied Surface Science* 502, 144109 (2020).
12. S. W. Seo, H. Chae, S. J. Seo et al., *Applied Physics* Letters **102**(16), 594003 (2013).
13. S. Lee, J. H. Han, S. H. Lee et al., JOM 71, 197-211 (2019).
14. S. H. Kim, S. Y. Song, S. Y. Kim et al., *NPJ Flexible Electronics* **6**(1), 21 (2022).
15. M. M. Hussain, Z. J. Ma and S. F. Shaikh, *The Electrochemical Society Interface* **27**(4), 65 (2018).