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Transparent OLEDs

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This thesis explores transparent organic light-emitting diodes (TOLEDs), a specialized subset of OLED technology that enables light emission from both sides of the device through the use of transparent electrodes. The purpose of the study is to provide a comprehensive overview of TOLEDs by examining their underlying principles, material components, fabrication methods, and practical applications. The research was conducted as a literature review, drawing from current academic and industrial sources to evaluate the latest developments in TOLED development. Particular attention is given to the design of transparent electrodes, such as indium tin oxide, graphene, and metal nanowires, which play a crucial role in balancing electrical conductivity with optical transparency. The study identifies key challenges in achieving mechanical flexibility, maintaining performance during large-area fabrication, and ensuring long-term stability through effective encapsulation. Applications in augmented reality, smart windows, and wearable electronics are highlighted as promising areas for TOLED implementation. The conclusions emphasize that while TOLEDs hold significant potential for next-generation optoelectronic devices, further innovation in materials and manufacturing processes is essential for widespread commercial adoption.

Key words: Transparent OLEDs, organic semiconductors, transparent electrodes, device fabrication, display technology

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Tämä kandidaatintutkielma käsittelee läpinäkyviä orgaanisia hohtodiodeja (TOLED), jotka muodostavat erikoistuneen osa-alueen OLED-teknologiassa. TOLED-laitteet mahdollistavat valon säteilyn molemmilta puolilta käyttämällä läpinäkyviä elektrodeja. Tutkimuksen tavoitteena on tarjota kattava yleiskuva TOLED-teknologiasta tarkastelemalla sen toimintaperiaatteita, materiaalirakenteita, valmistusmenetelmiä ja käytännön sovelluksia. Työ toteutettiin kirjallisuuskatsauksena hyödyntäen ajankohtaisia tieteellisiä ja teollisia lähteitä TOLED-kehityksen uusimpien edistysaskeleiden arvioimiseksi. Erityistä huomiota kiinnitetään läpinäkyvien elektrodien, kuten indiumtinaoksidin, grafeenin ja metallinanolankojen suunnitteluun. Elektrodimateriaalilla on keskeinen rooli sähköjohtavuuden ja optisen läpinäkyvyyden tasapainottamisessa. Työssä tunnistetaan keskeiset haasteet mekaanisen joustavuuden saavuttamisessa, suorituskyvyn säilyttämisessä suuraluevalmistuksessa sekä pitkäaikaisen vakauden takaamisessa tehokkaan kapseloinnin avulla. Sovelluksia lisätyn todellisuuden, älylasien ja puettavan elektroniikan alueilla korostetaan TOLED-teknologian lupaavina käyttökohteina. Johtopäätöksissä todetaan, että vaikka TOLED-laitteilla on merkittävää potentiaalia uuden sukupolven optoelektronisissa sovelluksissa, materiaalien ja valmistusprosessien jatkokehitys on olennaista niiden laajamittaisen kaupallisen käyttöönoton mahdollistamiseksi.

Avainsanat: läpinäkyvät OLEDit, orgaaniset puolijohteet, läpinäkyvät elektrodit, valmistusmenetelmät, näyttöteknologia

Table of contents

| | | |
|------------|--|-----------|
| 1 | Introduction | 5 |
| 2 | Organic Light-Emitting Diodes | 7 |
| 2.1 | Fundamentals and working principles of OLEDs | 7 |
| 2.1.1 | Structure and fundamentals | 7 |
| 2.1.2 | Working principle | 8 |
| 2.2 | OLED Materials | 9 |
| 2.2.1 | Substrate materials | 9 |
| 2.2.2 | Electrode materials | 9 |
| 2.2.3 | Emissive layer materials | 9 |
| 2.3 | Fabrication of OLEDs | 10 |
| 2.3.1 | Dry methods | 10 |
| 2.3.2 | Wet methods | 11 |
| 2.4 | Characterization | 12 |
| 2.4.1 | Optical characterization | 12 |
| 2.4.2 | Electrical characterization | 13 |
| 2.4.3 | Structural and compositional characterization | 14 |
| 2.5 | Different types of OLEDs | 14 |
| 2.5.1 | Bottom-emitting OLEDs | 15 |
| 2.5.2 | Top-emitting OLEDs | 15 |
| 2.5.3 | Transparent OLEDs | 16 |
| 3 | Transparent OLEDs (TOLEDs): Principles and design | 17 |
| 3.1 | Transparent Electrodes | 17 |
| 3.1.1 | Indium Tin Oxide | 17 |
| 3.1.2 | Graphene | 18 |
| 3.1.3 | Metal nanowires | 19 |
| 4 | Applications of TOLEDs | 20 |
| 4.1 | Future prospects of TOLEDs | 20 |
| 4.2 | Challenges and limitations of TOLEDs | 20 |
| 5 | Conclusions | 22 |
| | References | 23 |

1 Introduction

The acronym OLED stands for organic light-emitting diode. The technology is based on the integration of organic semiconductors (OSCs) that emit light as electrical charge passes through them. OLEDs are widely used in digital displays such as smartphone and television screens and have even surpassed traditional liquid crystal displays (LCDs) in these markets. However, LCDs still dominate in the field of budget and mid-range devices due to their lower manufacturing costs. Despite their higher price, OLEDs offer several advantages compared to LCDs. This includes higher energy efficiency and environmental friendliness. They can also allow for thinner, lighter and higher resolution devices in general [1].

OLED displays are composed of small individual pixels, each capable of generating their own light, leading to truer and richer colors when compared to a backlit LCD screen.

The first practical OLEDs were created in 1987 by chemists at Eastman Kodak using indium tin oxide (ITO) as the anode for the device, which is still widely used today due to its high transparency and good electrical conductivity. Traditional OLEDs are typically composed of a layer of organic materials sandwiched between a reflective cathode and a transparent anode supported by a substrate [2].

This thesis focuses on transparent organic light-emitting diodes (TOLEDs), in which both the anode and cathode are transparent, enabling light emission from both sides of the device, as illustrated in Figure 1 [3].

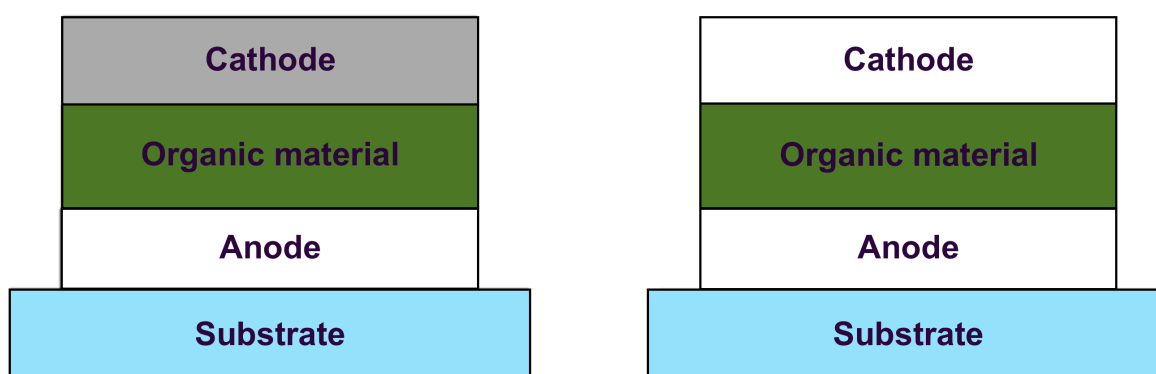


Figure 1. Schematics of a traditional OLED vs TOLED (simplified).

This literature review will begin by exploring the fundamentals and working principles of organic light-emitting diodes, including their materials and characterization methods. It will then provide an examination of transparent OLEDs, focusing on their principles, design, and structure. Finally, the review will discuss the future prospects and challenges associated with TOLED technology. AI has been used in the writing process of this thesis in the form of

Scopus AI for finding references, as well as Chat GPT for improving text cohesion and language quality. All content has been critically reviewed by the author to ensure academic integrity.

2 Organic Light-Emitting Diodes

OLEDs represent a significant advancement in display and lighting technology due to their ability to produce light intrinsically using the electroluminescent properties of OSCs. OLEDs rely on a diverse array of materials in order to take advantage of these properties and achieve efficient charge transport and device stability. The selection and optimization of these materials along with careful device fabrication and characterization play a key role in determining the performance and functionality of the OLED device.

2.1 Fundamentals and working principles of OLEDs

2.1.1 Structure and fundamentals

To understand the fundamentals and working principles of OLEDs it is crucial to understand the structure of an OLED device. A standard structure is illustrated in Figure 2.

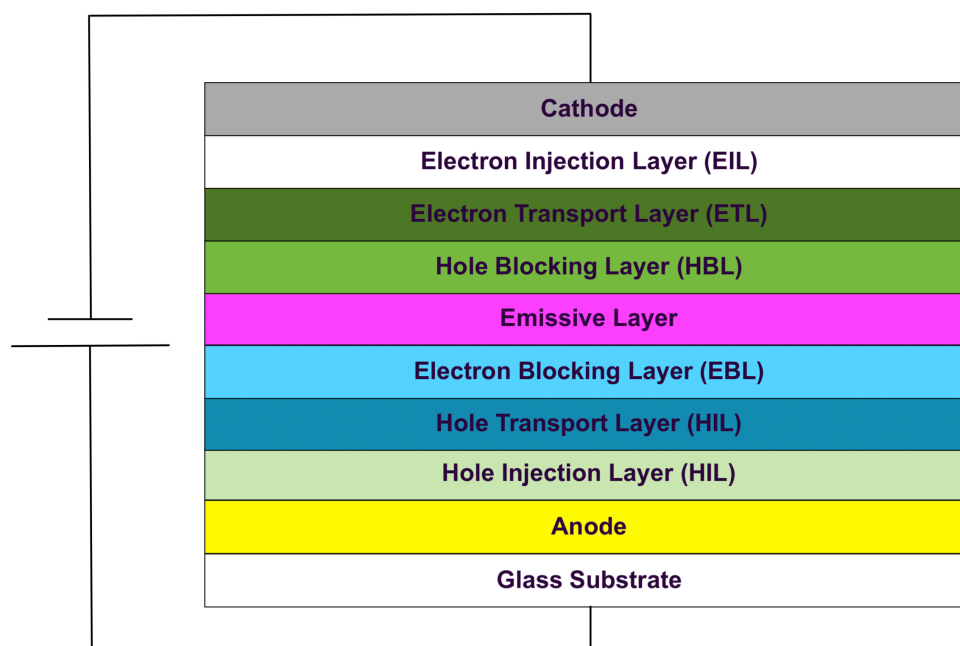


Figure 2. Multilayer OLED Structure [4].

Organic semiconductors serve as the key active materials in OLEDs, allowing the movement of electrical charge and enabling light generation. The term “organic” is used because several layers in the device structure, such as the hole transport and emissive layers, are composed of carbon-based materials, other layers may also be organic [5]. However, other layers in OSCs are responsible for three crucial processes: charge injection, charge transport and recombination of charge carriers (electrons and holes). These processes together are

responsible for electroluminescence (the emission of light). The most used OSCs in OLEDs include small molecule compounds and conjugated polymers which both share a π -conjugated molecular structure, meaning they have alternating single and double bonds that enable efficient charge transport and adjustable optical properties.

The emissive layer is responsible for the production of the visible light as the electrons and holes recombine. Charge transport layers in OLEDs enable for smooth movement of electrical charges between the electrodes and the emissive layer. These layers, which include the hole transport layer and the electron transport layer, help balance the flow of electrons and holes. This is crucial for preventing charge buildup and improving overall efficiency. Improved charge balance allows for maximum light emission and minimum energy loss between material interfaces.

The substrate and encapsulation layers are used to provide structural support, electrical insulation and protection from environmental factors. Of the two, the substrate serves as the foundation of the OLED, supporting the organic layers and the electrodes. The encapsulation layer shields the device from environmental exposure, which can degrade the organic materials and shorten the device's lifespan. Additionally, encapsulation can substantially prevent H_2O and O_2 from entering the device, and at the same time prevent leakage of toxic by-products, such as lead (Pb), into the environment.

Hole and electron injection layers facilitate efficient charge injection from the electrodes to the organic layers. Efficient selection of materials in these elements of the device enhance charge injection and help to reduce operating voltage [6].

2.1.2 Working principle

The basis of an OLED is a device that emits light when a voltage is applied to it. When electricity flows through an OLED, thin layers of organic material emit light. The primary function of OLED display technology is to precisely regulate and control the electrical current flowing through each pixel. As current-controlled devices, an OLED's brightness is related to the amount of applied current.

As seen in Figure 2, the organic layers are sandwiched between the electrodes. When a voltage is applied charge carriers are injected from these electrodes in the form of electrons from the cathode and holes from the anode. These charges are transported through the layers and recombined at the emission point. The recombination of holes and electrons excites the organic molecules, which then produce light as they return to their ground state.

2.2 OLED Materials

The performance, efficiency and lifespan of OLED devices are largely dependent on the materials used in their multilayer structure. OLEDs are composed of multiple organic and inorganic layers, that each serve a specific function. The careful selection of these materials is crucial for the optimization of the device. During this chapter the focus is on the materials used in the most important of these different layers.

2.2.1 Substrate materials

The substrate is a crucial component in OLEDs providing structural support and protection from the environment. An ideal substrate requires high transparency, low roughness, thermal stability and chemical resistance. Commonly used substrate materials include glass, plastics like PET (Polyethylene Terephthalate) and PEN (Polyethylene Naphthalate) and metal foils. Glass is used for its high stability, transparency and resistance to high temperatures, it is however brittle and therefore unsuitable for flexible applications. Plastics are lightweight and flexible but offer poor protection from heat, moisture and oxygen. Metal foils offer good thermal and chemical stability but feature higher surface roughness [7].

2.2.2 Electrode materials

An OLEDs anode must be transparent and extremely conductive to introduce holes into the organic layers. As it was in 1987, the most used anode material is still ITO. It features great electrical conductivity and up to 90% transparency to visible light [5]. Alternative but more rarely used materials include fluorine tin oxide (FTO) [8] and the composite material PEDOT:SS [9].

The cathode is responsible for injecting electrons into the emission layers. To ensure efficient electron injection, the cathode material should have a relatively low work function (the minimum energy required to remove an electron from the surface of the material). Cathodes are most often made of an unreactive material with a modest work function like a magnesium-silver alloy or aluminium combined with alkali metal compounds [5].

2.2.3 Emissive layer materials

The emissive layer emits visible light and is located in between the hole and electron transport layers. The primary emissive materials used in OLEDs include small molecules and conjugated polymers.

OLEDs using small molecules are known as Small-Molecule Organic Light-Emitting Diodes (SMOLEDs), their active organic layers (HTL, EML etc.) are typically less than 1 μm thick. The most commonly used SMOLED material is Tris(8-hydroxyquinolato)aluminium Alq_3 . Conjugated polymers are naturally conductive due to their alternating single and double bonds. When electrons and holes are injected, they create an excited state, which emits light as it decays. Their adjustable chemical structure and extended conjugation allows for enhanced solubility and better processability, making them ideal for OLED emissive layers. OLEDs based on these polymers are commonly referred to as POLEDs (polymer organic light-emitting diodes).

Many conjugated polymers used in OLEDs are engineered to have a low band gap, which can enhance their ability to emit visible light efficiently. However, their emission properties depend strongly on the molecular structure and the presence of specific functional groups. Common conjugated polymers used in OLEDs include polyaniline, polyacetylene, polythiophenes, polyfluorenes, and polyphenylenevinylene (PPV) [2], [5]. The stability of emissive materials also varies by color. Blue OLEDs in particular, degrade faster than red or green ones due to the higher energy of blue light, which accelerates material breakdown [6].

2.3 Fabrication of OLEDs

OLED fabrication can be broadly categorized into two distinct methods: dry and wet methods. Both of whom offer distinct advantages depending on the application.

The dry manufacturing method refers to the conversion of solid organic materials from a powder to a vapor, before condensing them onto a substrate. This is typically achieved in a high-vacuum environment.

The wet method involves dissolving organic materials in a solution or a condensed liquid phase. The wet solution is then applied to a substrate using techniques like spin coating, slit coating and inkjet printing, before drying and applying the next layer [10].

2.3.1 Dry methods

Vacuum thermal evaporation (VTE) is the dominant method for producing commercial OLED displays and lighting panels. This is because VTE offers superior efficiency, longer device lifespan, and higher overall performance compared to other techniques. Additionally, it is the most established and widely adopted manufacturing method in the OLED industry.

During the VTE process, a material is heated until it vaporizes, allowing the vapor to travel through a vacuum before condensing onto a substrate, forming a thin film.

VTE is commonly used for organic material deposition, as well as for metals like aluminium. The method relies on the concept of vapor pressure, which is the pressure exerted by a vapor in equilibrium with its solid or liquid phase at a given temperature. If the surrounding pressure is lower than the vapor pressure, more molecules escape from the material's surface, leading to evaporation. At equilibrium vapor pressure, the rate of evaporation and condensation is balanced.

This technique remains the most prevalent method for high-performance OLED fabrication due to its precise layer control, high efficiency, and well-established process stability [10].

2.3.2 Wet methods

Currently, dry processing methods dominate OLED manufacturing due to their ability to produce high-performance, long-lasting devices. However, maintaining the necessary high vacuum conditions is expensive and complex leaving room for improvement in the future. Wet processing techniques offer a promising alternative since they do not require a high vacuum, potentially reducing manufacturing costs and enabling large-area OLED production. Despite this advantage, wet methods have not yet matched the performance of dry processing. The key challenge lies in the formation of multilayer structures. During the application of new organic layers, solvents can dissolve previously deposited layers. This leads to poor film quality and reduced efficiency.

Inkjet printing is a promising manufacturing technique for OLEDs that offers a cost-effective and scalable alternative to traditional vacuum deposition methods. This method allows for the precise deposition of organic materials in liquid form onto a substrate. It is particularly advantageous for large-area OLED displays due to its high material utilization, direct patterning of pixels and high resolution [11].

Another common method is spin-coating. It involves applying solution made of organic material onto a rotating substrate. As the substrate spins with a high RPM, centrifugal force spreads the solution evenly across the surface. As the spinning continues, the solvent gradually evaporates, increasing the films viscosity and ensuring uniform thickness. Once fully dried, only a smooth, thin film remains on the substrate. Spin-coating offers several advantages including simplicity and cost-effectiveness, but the limitations in forming multilayer structures have limited the possibilities for widespread usage [12].

A promising future manufacturing process is that of the electrospray method, as it allows for fabrication of multilayer OLEDs. It works by atomizing organic materials into charged droplets using Coulomb repulsion. As these droplets travel toward the substrate, the solvent evaporates, leaving behind a solid thin film. Unlike conventional wet processes like spin coating or inkjet printing, electrospray reduces the risk of dissolving underlying layers, making it more suitable for multilayer OLED structures. This method also enables better control over film thickness and uniformity, which are critical for OLED efficiency and stability [13].

2.4 Characterization

The performance and reliability of OLED devices depend on several key factors. To ensure optimal device operation and longevity, OLEDs must undergo characterization using a plethora of different analysis techniques. By applying different testing techniques, researchers can identify performance limitations, optimize materials, and improve fabrication processes. For instance, external quantum efficiency (EQE) is a key parameter for evaluating OLED power and performance. It is defined as the ratio of the total number of emitted photons to the number of injected electrons. A higher EQE indicates a more efficient device [14].

2.4.1 Optical characterization

To measure EQE, the total emitted optical power P_0 is determined, considering only the light escaping from the OLED rather than the portion trapped inside the glass substrate. Since OLEDs emit light in multiple directions, accurate measurement requires specialized techniques. A calibrated silicon photodiode (Si PD) is commonly used to measure P_0 . The photodiode detects the emitted light and converts it into an electrical signal.

The optical performance of OLEDs is often also evaluated based on how the emitted light is perceived by the human eye. Luminance (cd/m^2) indicates the brightness of the display, while current efficiency (cd/A) and power efficiency (lm/W) describe how effectively electrical energy is converted into visible light. These values are typically derived from the device's electroluminescence spectrum combined with the photopic visibility curve, which represents human visual sensitivity across the visible range. To assess color performance, OLEDs are analyzed using CIE chromaticity coordinates, which define the emitted color within a

standardized color space. This helps in evaluating color purity, white point accuracy, and overall display quality [14].

The emission spectrum of OLEDs provides critical information about the color, intensity, and spectral purity of the emitted light, and is typically measured using spectrophotometric methods. One widely used approach involves reflection and transmission spectrophotometry, a fast and non-destructive technique well suited for analyzing thin organic films. This method enables accurate determination of the extinction coefficient (k) and refractive index (n) of multilayer OLED structures across a broad wavelength range. By examining both optical constants and layer thicknesses, it becomes possible to optimize device design and correlate structural properties with electroluminescent performance. Combined with spectral analysis of the emitted light, these techniques also support evaluation of key color characteristics, such as emission peak position, spectral bandwidth, and overall color quality, which are essential for achieving precise color tuning and high display performance [15].

2.4.2 Electrical characterization

The electrical behavior of OLEDs is typically evaluated through current–voltage (I–V) measurements, which provide insight into the charge injection properties and overall operating characteristics of the device. These measurements help identify key parameters such as the turn-on voltage, current density, and injection efficiency. These parameters influence both the power consumption and brightness of the display. In typical measurements, the voltage across the OLED is gradually increased while the current flowing through the device is recorded, usually in a dark environment. This allows for accurate assessment of how the device responds to forward bias and how efficiently it injects and transports charge carriers through the organic layers [14].

In addition to standard I-V analysis, more advanced techniques like impedance spectroscopy (IS) can be used to gain deeper insight into charge carrier dynamics in OLEDs. IS allows separate evaluation of parameters such as bulk conductivity, charge accumulation at interfaces, and recombination processes. By measuring how device capacitance changes with frequency at different voltages, it's possible to learn when carriers start to flow. The results also show how much charge builds up at interfaces, in addition to revealing whether some of the energy is lost through unwanted recombination [16].

2.4.3 Structural and compositional characterization

When studying the chemical composition and electronic structure of OLED materials, different spectroscopic methods like X-ray photoelectron spectroscopy (XPS) may be used. XPS reveals information about elemental composition, chemical bonding states, and interfacial properties within multilayer OLED structures. It works via X-rays, that excite the core electrons from the atoms. The kinetic energy of these emitted electrons can be measured which allows for determination of the element's binding energy and in-depth study of the materials [17].

Mathematical characterization and the application of analytical models can also be useful in predicting device behaviour and improving efficiency. Key mathematical methods include e.g. the use of equations such as Poisson's equation in calculating the electric field within the OLED device. Numerical simulations such as the Silvaco ATLAS [18] and Setfos by Fluxim can also be used to model device physics and compare theoretical predictions with experimental results. Setfos in particular, is designed specifically for simulating optoelectronic devices like OLEDs and organic solar cells. It allows users to analyse optical and electrical performance through multilayer stack modeling and drift-diffusion simulations, thus providing important information about device operation and performance characteristics [19].

2.5 Different types of OLEDs

OLEDs can be categorized based on how light exits the device, influencing their design, efficiency, and application areas. The three main types are bottom-emitting, top-emitting, and transparent OLEDs as seen in Figure 3.

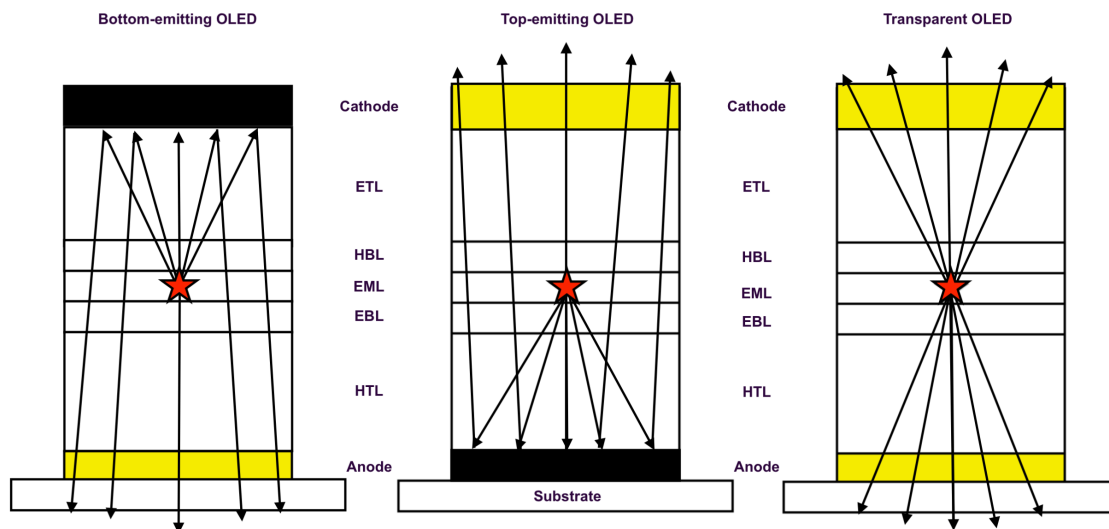


Figure 3. Schematical illustration of a bottom-emitting, a top emitting and a transparent OLED device.

2.5.1 Bottom-emitting OLEDs

Bottom-emitting OLEDs are currently the most used device structure for commercial applications like televisions and smartphones. In bottom-emitting OLEDs the light is emitted through the bottom substrate, which sits atop the transparent anode (usually made of ITO). One of the key advantages of bottom-emitting OLEDs is their compatibility with established manufacturing techniques, making them a cost-effective choice for large scale production. The transparent nature of the anode ensures good brightness and color accuracy, contributing to high quality displays. Light extraction efficiency can however be limited due to internal reflections within the substrate, and some emitted light may be absorbed by the bottom layers, reducing overall efficiency [20].

2.5.2 Top-emitting OLEDs

In contrast to bottom-emitting OLEDs, top-emitting OLEDs use a reflective anode and a semi-transparent or transparent cathode, allowing light emission from the cathode side. The use of ITO is not ideal for the cathode as its sputtering process can damage the organic layers below [21]. Instead, thin metal films such as pure Ag or other silver-based alloys are used. Top-emitting OLEDs are most commonly used in small size active-matrix OLED (AMOLED) displays. They allow for a higher aperture ratio in comparison to bottom-emitting ones which makes it easier to produce more efficient, high-resolution displays with a longer operational lifetimes [22].

2.5.3 Transparent OLEDs

Transparent OLEDs are a specialized type of OLED where both the anode and cathode are transparent, allowing light emission from both sides of the device. Unlike conventional OLEDs, which emit light in a single direction, TOLEDs provide high transparency when turned off and clear, high-contrast images when active. These features make them ideal for applications such as augmented reality, smart windows and heads-up displays. TOLEDs face fabrication challenges in selecting highly transparent, flexible and conductive electrode materials that still allow for high efficiency. ITO has been the traditional choice for transparent electrodes but is limited by its high cost and brittle nature. Recent advancements have introduced oxide/metal/oxide (OMO) structures, such as $\text{MoO}_3/\text{Au}/\text{MoO}_3$ electrodes, which achieve high transparency and maintain low sheet resistance, all while providing excellent mechanical durability, making them promising alternatives to ITO [23].

3 Transparent OLEDs (TOLEDs): Principles and design

TOLEDs represent a specialized type of OLED technology, characterized by their unique structure that includes transparent electrodes on both sides of the device. Unlike conventional OLEDs that emit light from only one side, TOLEDs enable dual-side emission. This makes them suitable for innovative applications such as augmented reality (AR) displays, smart windows, automotive displays, and wearable devices.

The defining feature of TOLEDs is the use of transparent conductive electrodes on both sides of the organic layers. This transparency allows users to see through the device when it is turned off and offers unique visual effects when it is active. However, achieving high transparency introduces significant challenges, including balancing optical clarity with electrical conductivity and managing light extraction losses. This leads to the design and selection of materials becoming critical factors affecting the overall device performance.

3.1 Transparent Electrodes

As mentioned, the two transparent electrodes are the components in TOLED devices setting them apart from regular OLEDs. A critical function of these electrodes is combining electrical conductivity and optical transparency. Ideal transparent electrodes should exhibit high transparency across visible wavelengths, low electrical resistance, flexibility, and mechanical durability. Achieving this balance of properties remains a key challenge in electrode development.

ITO is traditionally the most widely used transparent electrode material. However, the scarcity and high cost of indium, along with the brittle nature of ITO films, have driven researchers to explore alternative electrode materials. These alternatives include conductive polymers, carbon-based materials (graphene and carbon nanotubes), and metal-based materials such as silver nanowires. Each material class has its own distinct advantages: metal-based electrodes offer superior conductivity, conductive polymers provide flexibility and ease of processing, and carbon-based electrodes balance high flexibility with environmental sustainability and cost-effectiveness [24].

3.1.1 Indium Tin Oxide

ITO is currently the most widely used transparent electrode material in OLED devices because of its high optical transparency (around 90% in the visible range) and excellent

electrical conductivity. Due to these favorable properties, ITO has become the standard choice for transparent anodes in OLED fabrication, enabling efficient hole injection into organic layers [24]. The widespread use of ITO is supported by its established manufacturing processes and compatibility with existing OLED technologies

Despite its widespread use, ITO presents notable challenges, especially for emerging OLED applications that require flexibility and dual-side transparency. Firstly, the key element in ITO, Indium is scarce and costly, leading to economic and sustainability concerns.

Additionally, ITO films are inherently brittle, which limits their mechanical flexibility, restricting their use in flexible or bendable OLED devices.

Another significant limitation arises when considering ITO for use as a transparent cathode. Depositing ITO typically involves sputtering, which can damage the sensitive organic layers beneath, negatively affecting device performance and lifetime. Due to this, alternative materials such as thin metal films, graphene, or OMO structures have been developed and implemented as transparent cathodes [25].

3.1.2 Graphene

Graphene has emerged as a highly promising alternative electrode material for transparent OLEDs, addressing several limitations associated with traditional electrode materials. It consists of a single atomic layer of carbon atoms arranged in a two-dimensional honeycomb structure, resulting in exceptional properties including high transparency (over 90% in the visible spectrum), superior mechanical flexibility, and excellent electrical conductivity. These properties allow their integration into flexible and wearable OLED devices without the brittleness issues associated with ITO.

What makes graphene an attractive cathode material when compared to ITO is the possibility of deposition using low-energy techniques. This minimizes the damage done to underlying OLED structures, thus preserving device performance and lifetime in comparison to ITO.

A drawback of pristine graphene is its relatively high sheet resistance and a suboptimal work function for electron injection in OLED cathodes. To address this, doping methods have been developed to modify graphene's electrical and electronic properties. For example, doping with alkali metals such as caesium effectively lowers its work function, significantly enhancing electron injection capability. These chemically doped graphene electrodes demonstrate improved charge transfer dynamics, enabling highly efficient electron injection into the emissive organic layers. Doped graphene provides an effective transparent cathode option

suitable for high-performance TOLEDs and has high potential for becoming the transparent cathode of choice for next-generation OLED technologies [26].

3.1.3 Metal nanowires

Metal nanowires, especially ones made of silver and copper, have attracted considerable attention as transparent electrodes for OLED applications due to their excellent material properties. They offer high optical transparency (typically above 85% across visible wavelengths), outstanding electrical conductivity, and excellent mechanical flexibility. The fundamental structure of metal nanowire electrodes typically involves a randomly oriented network of nanowires fabricated through solution-based coating processes. This method provides cost-effective, and scalable production compared to the conventional deposition methods used for ITO electrodes.

Despite these advantages, metal nanowire electrodes face certain challenges. Silver nanowires have limitations related to high material costs and stability concerns, including oxidation or corrosion under environmental exposure. Copper nanowires provide a more economical alternative, but they too struggle with oxidation and require additional protective coatings to prevent it and to enhance their long-term stability. Effective solutions involve the deposition of thin protective layers or encapsulation materials, significantly improving durability and device lifespan without compromising transparency or conductivity. Another issue arises from achieving uniform deposition and effective surface smoothness for compatibility with the sensitive organic layers. Research efforts are currently focused on refining deposition methods, protective coatings, and network optimization to address these challenges, highlighting metal nanowires as one of the most promising alternatives to conventional transparent electrode materials for next-gen OLED applications [27].

4 Applications of TOLEDs

TOLEDs represent a significant advancement in display technology, combining optical transparency with vibrant, high-quality images. These characteristics enable a variety of exciting future prospects, opening new opportunities beyond conventional OLED technologies. Despite their promising capabilities, TOLEDs face certain challenges and limitations that must be addressed before they can take the leap to be fully commercially viable.

4.1 Future prospects of TOLEDs

The aspect of dual-side emission and optical transparency in TOLEDs allows for a variety of advanced applications beyond current display technologies. An emerging application with substantial potential is in AR where TOLED displays can seamlessly overlay visual information onto real-world environments. This creates a more immersive and interactive user experience, ideal for consumer electronics, navigation systems, and training simulators. These AR displays not only enhance the interaction between users and their environment but also improve safety and usability, particularly in automotive applications. Integration into windshields or vehicle windows offers real-time information such as navigation prompts, vehicle diagnostics, or safety alerts without obstructing the driver's view. Such developments have the potential to enhance road safety and provide drivers with intuitive access to critical information.

Another promising area is smart window technology. TOLED-integrated smart windows can serve dual purposes. They can function as transparent glass during daytime whilst also displaying interactive information as needed. This innovation could significantly enhance architectural design, as well as providing energy efficiency through adjustable transparency and dynamic visual content.

The flexibility of TOLEDs opens possibilities for wearable electronic devices. Lightweight and bendable TOLED displays can be integrated directly into clothing, watches, or medical devices, delivering advanced usability combined with comfort and aesthetic appeal [28].

4.2 Challenges and limitations of TOLEDs

Despite their promising potential and wide array of advanced applications, transparent OLEDs face several significant challenges limiting their broader commercial implementation. One major issue arises from balancing high transparency with sufficient electrical

conductivity in transparent electrodes. Typical transparent electrodes like ITO struggle with flexibility and brittleness, while alternative materials often face issues related to high electrical resistance or limited transparency.

A specific approach to address these electrode-related challenges is the development of micro-mesh patterned electrodes. Micro-mesh patterned electrodes significantly enhance optical transparency without severely compromising electrical performance. However, these structures must be carefully designed and fabricated to prevent issues such as uneven current distribution, local hotspots, or reduced electrode uniformity. Maintaining uniformity is crucial because uneven thickness or defects in electrode layers can negatively affect charge injection, resulting in reduced OLED lifetime and efficiency.

The manufacturing processes required for creating transparent electrodes add complexity and production costs. Precise control during fabrication becomes crucial, as minor deviations can have a substantial impact on device performance. Effective encapsulation techniques also remain essential, as transparent electrodes, particularly metal-based electrodes, can be prone to oxidation or corrosion over time if exposed to moisture or air. Addressing these concerns typically involves additional protective coatings or encapsulation methods even further increasing complexity and cost [29].

Effective encapsulation remains a critical and ongoing challenge for TOLED devices. Due to the highly reactive nature of organic materials used in OLEDs, being subjected to oxygen or moisture can lead to rapid degradation, causing dark spots, reduced luminance, and eventual device failure. Advanced encapsulation technologies, such as thin-film encapsulation (TFE), have been developed to address these stability concerns. Techniques like atomic layer deposition (ALD) and plasma-enhanced chemical vapor deposition (PECVD) provide ultra-thin barrier layers with improved impermeability to oxygen and water vapor, significantly enhancing device lifetime. The implementation of these encapsulation methods is however technically demanding and increases overall production costs, presenting a challenge for widespread commercialization [30].

Significant progress has been made, but achieving the ideal balance between electrode performance, mechanical flexibility, cost-effective manufacturing, and robust encapsulation remains a critical barrier between widespread commercial adoption of TOLED technology. Addressing these limitations through continued innovation and materials research will be crucial to enabling their widespread implementation.

5 Conclusions

This thesis has explored the fundamentals, materials, fabrication methods, and characterization techniques of OLEDs, with a particular focus on their transparent variant, TOLEDs. Through a review of recent literature, it has become clear that TOLEDs offer significant potential for next-generation optoelectronic applications due to their ability to emit light from both sides while maintaining high levels of transparency.

The study showed that careful selection and optimization of materials is essential for achieving high-performance OLEDs. In particular, the design of transparent electrodes plays a key role. These components must balance optical transparency, electrical conductivity, and mechanical flexibility to ensure reliable and efficient operation. ITO remains the industry standard for transparent electrodes. It has its drawbacks, particularly in flexible and wearable applications. To address these issues, alternative materials such as graphene, metal nanowires, and oxide-metal-oxide structures are being actively explored as promising solutions.

Both dry and wet fabrication techniques were presented, with particular attention to newer approaches like electrospray deposition and inkjet printing, which hold promise for scalable, cost-effective manufacturing of complex OLED structures. The importance of accurate and comprehensive characterization was emphasized, including optical, electrical, and structural methods, all of which are essential for understanding and improving device performance.

Although TOLEDs offer exciting opportunities in fields like augmented reality, smart windows, and wearable electronics, several challenges must still be addressed. These include improving electrode materials, achieving reliable multilayer deposition in solution-processed devices, and ensuring long-term stability through effective encapsulation.

In conclusion, transparent OLEDs represent a promising path forward in display and lighting technologies. Continued research and innovation in materials science, device engineering, and scalable manufacturing will be key to unlocking their full commercial potential and enabling their integration into everyday technologies.

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