



**UNIVERSITY
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Organic light emitting transistors (OLETs)

the future of optoelectronics

Materials engineering/Department of Mechanical and Materials Engineering

Bachelor's thesis

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Organic light-emitting transistors (OLETs) represent a cutting-edge division of organic optoelectronic devices that combine the functionalities of organic field-effect transistors (OFETs) and organic light-emitting diodes (OLEDs). These devices have garnered significant attention due to their potential to streamline the fabrication processes of next-generation pixel circuits and miniaturized photonic devices. The unique architecture of OLETs integrates electrical switching and light-emitting capabilities into a single device, making them promising candidates for advanced display technologies and electrically pumped lasers.

Recent advancements in OLET technology include recently developed emissive high-mobility organic semiconductors and innovative device configurations such as bulk heterojunctions, asymmetric source-drain electrodes as well as layered heterojunctions. These innovations have significantly enhanced the performance and functionality of OLETs, positioning them as viable solutions for highly integrated organic electronics and optoelectronics. Despite the slow initial progress, the field has seen remarkable breakthroughs that may herald a new era of OLET development.

The fundamental working principles, materials, and device architectures of OLETs are critical to their performance. Researchers are focused on addressing challenges related to device stability, efficiency, and integration into mainstream technologies. As the technology advances, OLETs are expected to play a pivotal role in the future of optoelectronic applications, offering new opportunities for both scientific exploration and practical implementation.

In this thesis the working principles, materials, fabrication, device architectures, characteristics, applications in displays and sensing, and challenges are addressed.

Keywords: Organic light emitting transistors (OLETs), Organic semiconductors (OSCs), Display technology, sensing, Organic light emitting diodes (OLEDs)

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Orgaaniset valoa emittoivat transistorit (OLETit) edustavat orgaanisten optoelektronisten laitteiden huipputeknologiaa, joka yhdistää orgaanisten kenttävaikutustransistorien (OFETien) ja orgaanisten valoa emittoivien diodien (OLEDien) toiminnot. Nämä laitteet ovat herättäneet suurta huomiota niiden potentiaalini vuoksi yksinkertaistaa seuraavan sukupolven pikselipiirien ja pienoiskoossa olevien fotonisten laitteiden valmistusprosesseja. OLETien ainutlaatuinen arkkitehtuuri yhdistää sähköisen kytkennän ja valon emittoinnin yhteen laitteeseen, mikä tekee niistä lupaavia ehdokkaita kehittyneisiin näyttöteknologioihin ja sähköisesti pumpattuihin lasereihin.

Viimeaikaiset edistysaskeleet OLET-tekniologiassa sisältävät äskettäin kehitettyjä emissiivisiä korkean liikkuvuuden orgaanisia puolijohteita ja innovatiivisia laitekonfiguraatioita, kuten bulkkiheteroliitoksia, epäsymmetrisiä lähde-viemärielektrodeja sekä kerrostettuja heteroliitoksia. Nämä innovaatiot ovat merkittävästi parantaneet OLETien suorituskykyä ja toiminnallisuutta, mikä tekee niistä varteenotettavia ratkaisuja erittäin integroituihin orgaanisiin elektroniikka- ja optoelektronikkasovelluksiin. Vaikka alkuvaiheen kehitys oli hidasta, alalla on tapahtunut merkittäviä läpimurtoja, jotka voivat merkitä uutta aikakautta OLETien kehityksessä.

OLETien toiminnan peruseräatteen, materiaalit ja laitteiden arkkitehtuurit ovat ratkaisevan tärkeitä niiden suorituskyvyn kannalta. Tutkijat keskittyvät ratkaisemaan haasteita, jotka liittyvät laitteiden vakauteen, tehokkuuteen ja integrointiin valtavirran teknologioihin. Teknologian edistyessä OLETien odotetaan näyttelevän keskeistä roolia optoelektronisten sovellusten tulevaisuudessa, tarjoten uusia mahdollisuuksia sekä tieteelliseen tutkimukseen että käytännön sovelluksiin.

Tässä tutkielmassa käsitellään OLETien toiminnan periaatteita, materiaaleja, valmistusta, laitteiden arkkitehtuureja, ominaisuuksia, sovelluksia näytöissä ja antureissa sekä haasteita.

Avainsanat: Organic light emitting transistors (OLETs), Organic semiconductors (OSCs), Display technology, sensing, Organic light emitting diodes (OLEDs)

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1 Introduction

Organic light emitting transistors (OLETs) represent a potentially disruptive technology in the fields of display and sensing, characterized by their planar field-effect architecture which integrates photon management within organic materials, electroluminescence generation, and electrical switching. OLETs rely on organic semiconductors (OSCs), which are carbon-rich compounds having tailored structures optimized for charge mobility and luminescent properties. These materials' ability to perform multiple functions simultaneously allows multifunctional organic devices with simple structures and minimal active materials to be manufactured. Excitons, or mobile molecular excited states, play a crucial role in light emission through radiative recombination in these materials. Organic semiconductors' compatibility with low-cost, large-scale deposition methods on various substrates, such as metal foils, plastic, and glass, further enhances their appeal for electronic and photonic applications.^{1,2}

The promise of OLET technology lies in its unique combination of features. Unlike traditional OLEDs, OLETs can be switched on and off solely by applying a potential, independent of current density. This allows lower quality TFT backplanes to be used to drive OLET frontplanes, significantly reducing costs and facilitating flexible display technologies. Additionally, the integration of electrical switching and light generation into a single device structure simplifies the driving circuit, decreasing the complexity of manufacturing. Additionally, this will reduce the cost of the manufacturing. OLETs also offer potential improvements in the lifetime. In addition, due to optimized charge carrier balance and different driving conditions, the efficiency of organic light-emitting materials are potentially higher when compared to the standard OLED architectures.^{1,2}

OLETs share commonalities with other organic electronic devices such as OFETs and OLEDs. They typically employ π -conjugated organic species, insulators, and conductive materials for active channels, dielectric layers, and electrodes, respectively. The structural similarities between OLETs and OFETs include their three-terminal device configuration and the use of similar materials and device geometries. However, OLETs require the coexistence of accumulation layers for holes and electrons inside the conductive channel to achieve light emission via radiative electron-hole recombination.^{1,2}

One of the key advantages of OLETs over inorganic counterparts is the tunability of emission colour through molecular and supramolecular engineering. This feature, combined with the

potential for low-cost, large-scale manufacturing on a variety of substrates, positions OLETs as a promising technology for next-generation displays and sensing applications.^{1,2}

In Chapter 2 this thesis will address the working principle of OLETs as well as the structure and materials are used in OLETs. In addition, Chapter 2 will address the different types of OLETs and their modelling and simulation. In Chapter 3 fabrication, the different processes and encapsulation of OLETs is addressed. The characterization of both optical and electrical properties is addressed in Chapter 4. In Chapter 5 the applications of OLETs as well as challenges and future development is addressed. Chapter 6 concludes this thesis.

2 Design

2.1 Working principle of OLETs

The active part of an OLET is composed of an organic semiconductor material which acts as a channel. At the opposite endings of the channel there are two electrodes: the drain and the source. channel length (L) is the clearance between the drain and the source. Additionally, the traverse distance is called the channel width (W). Underneath the channel, there is a third electrode called the gate which dictates the portion of the channel that is used in the conduction. The channel is also connected to the dielectric layer that is functioning as a capacitor. Furthermore, the dielectric layer acts as a part that modulates the allowed current through gate voltage.¹

OLETs use the efficient radiative recombination of holes and electrons. In biased conditions this recombination causes light emission from the transistor channel. From a rudimentary viewpoint this offers the probability of direct visualization of recombination characteristics and ambipolar transport.¹

OLETs are divided into two different categories: unipolar and ambipolar. For unipolar OLETs the charge transport through the channel is dominated by either the hole or the electrons. These can also be called p- or n-channel OLETs. For hole-dominated devices, holes are injected into the transistor channel and can travel through it. Electrons on the other hand are also injected into the transistor channel but stay close to the electrode since travel is hard in a hole-dominated device. For this reason, the recombination happens close to the electrode that injects the electrons. The roles will reverse if the device is electron-dominated. For ambipolar OLETs the channel can accumulate both holes and electrons. The proportion for them can be changed with the gate voltage (V_G). Depending on the gate voltage the place where recombination happens changes.³

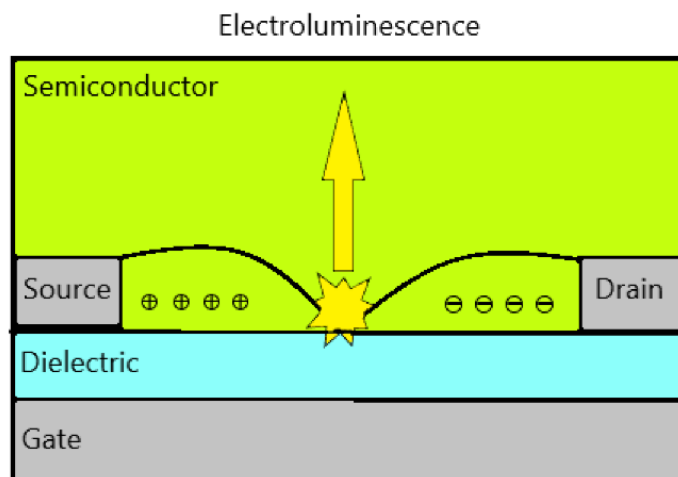


Figure 1. The working principle and illustration of a single layer OLET.

2.1.1 Energy levels

In organic semiconductors, charge localizations occur at the level of individual molecules. The key molecular orbitals in these systems are the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO). These orbitals functions are similar to the valence and conduction bands in inorganic semiconductors. Optimizing the injection process involves aligning the work function of the anode metal with the HOMO of the organic semiconductor to facilitate hole injection. Similarly, for efficient electron injection, the work function of the cathode metal must be matched with the LUMO of the organic semiconductor.^{1,4}

When the organic semiconductor is in contact with the metal electrodes, the band structure of the organic material and the two metal electrodes can be simplified as is shown in Figure 2 The vacuum level represents the energy level where electrons can escape the atoms. The distance from the HOMO level to the vacuum level is defined as the ionization energy (I) and the distance from the LUMO level to the vacuum level is defined as electron affinity (A). When a voltage is applied, holes and electrons are injected from the metal electrodes into the organic semiconductor. If the HOMO level is lower than the metal work function (Φ), the energy gap between the metal work function and the HOMO level is called the hole injection barrier (Φ_B^p). Conversely, if the LUMO level is higher than the metal work function, the energy gap between them is called the electron injection barrier (Φ_B^n).^{1,4}

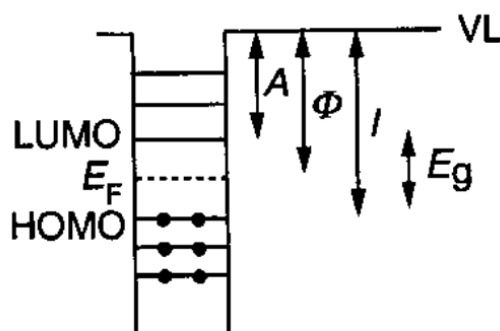


Figure 2. Simplified electronic structure and energy levels while organic semiconductor and electrode are in contact. E_g : Homo-Lumo bandgap. [4], Adapted with permission from Wiley.

2.2 Structure of OLETs

OLET production offers two primary architectures: top contact and bottom contact configurations. The main difference in them is their fabrication order. In bottom contact setup, source/drain contacts are applied before depositing the semiconductor layer, yielding a bottom contact device. Conversely, in the top contact configuration, the semiconductor layer is deposited first, followed by the source/drain contacts, resulting in a top contact device. Another approach involves constructing the transistor atop the semiconductor layer, known as top gate architectures. Here, the dielectric layer and the gate contact are deposited in sequence on either of the two source-drain contact configurations.¹ Examples of the four OLET architectures are depicted in Figure 3.

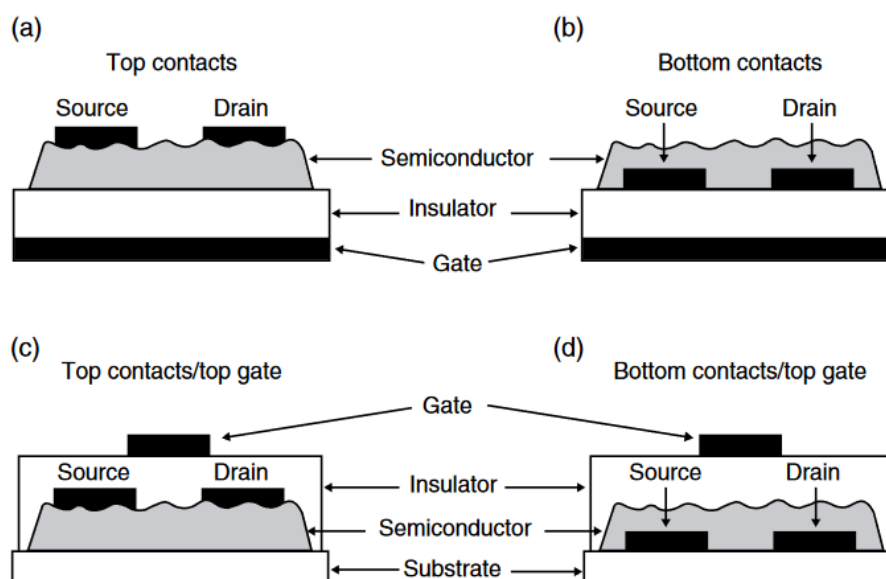


Figure 3. Four possible OLET architectures. (a) top contacts, (b) bottom contacts, (c) top contacts with top gate and (d) bottom contacts with top gate. [1], Adapted with permission from Wiley.

In the bottom gate-bottom contact (BG-BC) setup, the dielectric layer directly holds both the source as well as drain electrodes. The gate contact, typically serving as the substrate, lies beneath the dielectric layer, with the active material grown atop it. Unlike the bottom gate-top contact (BG-TC) configuration, this arrangement involves three interfaces operating within the same region: organic semiconductor/dielectric, organic semiconductor/dielectric and contacts/dielectric. The presence of electrodes also makes it very hard if not impossible to treat the surface of the dielectric layer, in BG-BC configuration, to improve OLET performance.¹

In the BG-TC configuration, the organic semiconductor layer is positioned below the drain and source electrodes. Beneath them lie the gate electrode and the dielectric layer. The gate electrode is also able to function as the substrate. This geometry ensures a clear separation between the injection zone: contacts/organic semiconductor and the conducting zone: organic semiconductor/dielectric. Additionally, the chemical functionalization of the dielectric surface needed to regulate growth of the active semiconductor layer is a straightforward as well as efficient process in this configuration.¹

The top contact OLETs depicted in Figure 3 typically demonstrate the least contact resistance, primarily due to the larger contact area between metal-semiconductor afforded by this setup. However, in the top contact configurations a significant portion of contact resistance stems from access resistance. It arises because the charge carriers need to traverse from the source contact atop the film down the semiconductor-dielectric interface where the channel is. They also need to go back to the drain contact for extractions. In the bottom contact architecture, because the contact and the channel reside on the same plane, access resistance is circumvented since.¹

Among the top gate OLET architecture as depicted in Figure 3, the top contact-top gate layout is deemed advantageous over bottom contact-top gate devices due to the avoidance of access resistance. However, it's essential to acknowledge that both top gate setups encounter additional challenges. These include concerns about semiconductor top surface roughness and how the interface in the middle the surface of the semiconductor layer and of the insulator is established so that it is stable. For instance, if the top insulator material is solution deposited, it could potentially harm the underlying semiconductor layer. Furthermore, with regards to align the channel and the top gate contacts, meticulous attention is required to ensure that the gate has contact the device in its entirety. Failure to achieve complete alignment or coverage can introduce additional contact resistance due to unfated areas in the semiconductor on either one or both ends of the contact.¹

2.3 Materials used in OLETs

2.3.1 Dielectric layer

In a typical thin-film OLET the dielectric layer is situated in between the organic semiconductor and the gate electrode. The dielectric layer serves to electrically isolate the gate from the other two electrodes, a prerequisite needed in order to facilitate the field-effect. Additionally, at the interface polarization happens, thereby enabling transport within the organic active layer. In addition, to facilitate transport the thickness of the dielectric needs to be at least an order of magnitude smaller than the channel length.^{1,5}

It is feasible to engineer improvements in OLET properties through dielectric manipulation. Dielectrics possess the ability to impede charge transport within themselves. When subjected to an electric field, the layer undergoes a redistribution of charges, resulting in a polarization effect. In more conventional framework, when the two electrodes are separated by a distance d and have a bias voltage V applied across them, it induces an electrical field E as:

$$E = V/d$$

with a charge per unit area Q given by:

$$Q = \varepsilon_0 E = \varepsilon_0 V/d$$

where ε_0 is the free space permittivity. With this it is possible to define C_i as the capacitance per unit area:

$$C_i = Q/V = \varepsilon_0/d$$

If a dielectric material is placed between the electrodes, it increases value of capacitance by an order of k , which is the dielectric constant. Due to material polarization the capacitance per unit area can be expressed as:

$$C_i = \varepsilon_0 k/d.$$

Other key factors that should be considered when choosing the dielectric material are control interfaces, maximum electrical displacement, leakage, processability, transparency, stability and reliability.^{1,5}

The dielectric material can be divided into two categories: inorganic dielectric materials and polymer dielectrics. For inorganic the most commonly used one is silicon dioxide SiO_2 as it has been used for decades. Because of its long production it is possible to fabricate very thin, high quality and smooth wafers. However, SiO_2 has a low dielectric constant (3.9) and new dielectric materials with increased k values are required. This is to ensure that the dielectric properties meet requirements and high-performance organic and inorganic transistors can be manufactured. Figure 4 showcases other options to replace SiO_2 and some of them such as Al_2O_3 and TiO_2 have already been used in literature. It is also important to remember that the dielectric layer needs to be optically transparent which may render some of the materials shown in Figure 4 to be invalid for this application. High- k dielectrics offer significant promise for advancing the performance of OLETs. However, the interface between the organic layer and inorganic dielectric layer often contains numerous hydroxyl groups which serve as defects and trapping sites. These factors can be detrimental to device performance, resulting in issues such as hysteresis behaviour, low charge mobility and poor stability. Various methods to passivation have been suggested and effectively deployed to address this limiting factor.^{1,5}

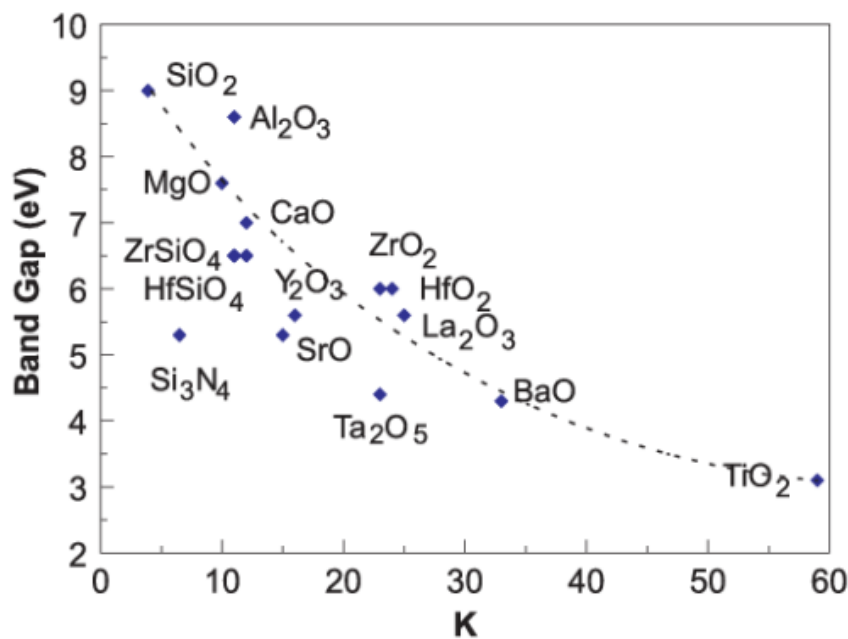


Figure 4. Dielectric permittivity of inorganic materials. Bandgap as a function of the dielectric constant. Reproduced from [5].

Polymer dielectrics have found extensive application in OLET devices primarily for two key reasons: firstly, they tend to exhibit minimal or negligible traps densities at the interface, thereby facilitating the development of high-performance devices. Secondly, they offer the advantage of enabling device fabrication on substrates that are flexible, a crucial feature if they

are to be applied in wearable and conformable electronics. Thirdly the use of polymer dielectrics typically ensures good mechanical properties and straightforward fabrication processes. However, when employing polymer dielectrics, certain considerations come into play. The first one is process compatibility. The fabrication process may necessitate high temperature treatments, which, depending on configuration, can potentially impact both the active organic layer and the substrate. The second one is surface hydroxyl groups. These groups are often present on the surface and may require a passivation layer at the interface between the dielectric and the organic semiconductor. Failure to address this can cause similar problems as in inorganic dielectrics. Some of the used materials are benzocyclobutene (BCB), polyethylene, poly(methyl methacrylate) (PMMA) and parylene. Of these PMMA is the most used, because it allows for a smooth surface and creates the small amount of trap sites at the interface.^{1,5}

2.3.2 Organic semiconductors

Organic semiconductor plays a critical role in the charge transportation and light emission. However, not all OSCs act similarly. Some can only be used for light emission or charge transportation and others can be used for both. For this reason, selecting OSC material that meet the requirements for use in OLETs is a nontrivial task. It involves selecting a material that can do both roles or material combinations that enable balanced charge injections, transport and recombination to achieve optimal device performance.^{1,3}

Materials, that can do both roles, require to have both high photoluminescence quantum yield (PLQY) and high carrier mobility to unlock their likely usage in active-matrix full-colour displays, sensing, integrated photonic circuitry as well as potentially electrically driven organic lasers. Nonetheless, in many instances, high carrier mobility OSCs, often caused by robust intermolecular π - π stacking, encounter luminescence quenching in solid state, which can be linked to either exciton quenching phenomena or singlet fission. For instance, while rubrene, tetracene and pentacene exhibit better field-effect transistor (FET) mobility, their emission is either low or non-existent.^{1,3}

The coupling of electrons between adjacent molecules and polaronic relaxation energy, in organic systems, are critical factors affecting the likelihood of charge transport between molecules. These factors strongly rely on the relative arrangement of the interacting units and the specific molecule.¹

OSC systems in field-effect device structures having high charge mobility often exhibit robust interchain/intermolecular interactions, particularly notable in low-molecular-weight oligomers. However, this characteristic can pose challenges when these materials are integrated into optoelectronic devices. Indeed, rigid oligomers typically exhibit lower luminescence efficiency in the solid state compared to polymers like polyphenylene vinylenes and polyfluorenes.¹

While molecular design and integrations of OSC materials are considered the primary pathway to enhancing the device performance of organic field-effect transistors (OFETs), historical efforts in molecular design predominantly prioritized carrier transport over the enhancement of multifunctional attributes like light emission and light sensing.¹

Effective implementation of these well-established strategies in molecular design can significantly enhance the exploration efficiency of semiconductors that emit light. Structured studies on typical OFETs revealed that OSC properties can be finely tuned by adjusting key parameters. One of the parameters are the energy levels that can be tailored to ease carrier injections from contacting electrodes into semiconductors, modulating carrier trapping at the interface of dielectric-semiconductor, and influencing carrier recombination and exciton separations in the conductive channel. The second is intermolecular packing, interaction and overlapping can be manipulated to make charge transport smoother. Luckily, numerous strategies for molecular design have emerged in the last few years to adjust these properties, with light-emission being of particular focus. Notably, because there are existing carrier-transport materials, it provides a shortcut into introducing specific functional groups. It is possible to leverage these strategies and obtain novel multifunctional materials.¹

As an example, viable approach to achieve ambipolarity on novel OSCs involves synthesizing copolymers or small molecules containing both electron-acceptor (A) as well as electron-donor (D) moieties. The interchain D-A interactions enhances intermolecular interactions, thereby reducing the π - π stacking length and increasing the capability of self-assembly. In theory, if the charge-transfer process is directed towards the most emissive moiety or if moiety that are dedicated to exciton formations are introduced with efficient radiative deactivation, it becomes feasible to engineer functionalities such as a single molecular or polymeric unit with light emission capabilities as well as hole/electron charge transport.¹

Examples of these materials can be seen in Table 1. Of the materials seen in Table 1, poly(9,9-di-n-octylfluorene-alt-benzothiadiazole (F8BT) has been used in polymeric single-layer OLETs and has demonstrated superior performance for practical applications. F8BT serves as an

efficient green-light emitter, in solid films, boasting photoluminescence efficiencies ranging from 50% to 60%. F8BT exhibits an ionization potential of 5.9 eV and a relatively high electron affinity of 3.3 eV due to the electron-withdrawing nature of the benzothiadiazole group (BT).¹

Table 1. Summary of various single layer OLET materials and their performances. Reproduced from [3] with permission from Wiley.

| Single-layer LETs | | | | | | |
|---|------------------|---|---|---------------------------------------|---|--|
| Material | Color | μ_{hole} [cm ² V ⁻¹ s ⁻¹] | μ_{electron} [cm ² V ⁻¹ s ⁻¹] | ON/OFF ratio | Max power [W] or max luminance [cd m ⁻²] | EQE [% or cd A ⁻¹] at max luminance |
| F8BT | Green-Yellow | 0.0006 | 0.00005 | <100 | – | 0.6 |
| F8BT (split-gate) | Green-Yellow | 0.000094 | 0.000025 | <100 | 609 cd m ⁻² | 1.3 |
| F8BT | Green | <0.001 | <0.001 | <10 | 8000 cd m ⁻² | 4 |
| Rubrene and tetracene (single crystals) | Orange and green | 0.82 and 2.3 | 0.27 and 0.12 | =10 ² and =10 ⁵ | – | 0.002 and 0.02 |
| EFIN | Blue | 0.000006 | – | ≈10 ⁴ | – | 0.2 |
| BSB-Me (single crystal) | Blue | 0.0001 | 0.01 | ≈10 ³ | – | 0.2 |
| P3V2 (single crystal) | Blue | 0.11 | 0.013 | ≈10 ⁴ | – | 0.1 |
| Super Yellow (PDY-132) | Yellow | ≈0.0003 | ≈0.0003 | ≈10 ⁴ | 43 cd m ⁻² | 0.19 |
| F8BT | Green-Yellow | 0.0007–0.0009 | 0.0007–0.0009 | <100 | – | 0.75 |
| F8TBT | Red | 0.0005 | 0.00003 | <100 | 80 nW | 0.4 |
| MEH-PPV | Yellow-Red | – | – | 10 ⁵ | – | – |
| Tetracene (film) | Yellow | 0.005 | – | 10 ⁶ | 45 cd m ⁻² | 0.0024 cd A ⁻¹ |
| BTBT-C ₁₀ | UV | 6 | – | ≈10 ⁹ | ≈1 μW | 0.003 |
| Ph-BTBT-C ₁₀ | Blue | 2 | – | ≈10 ⁷ | ≈0.08 μW | 0.0006 |
| PDI-C13 | Red | – | – | – | ≈02 nW, 42 cd m ⁻² | 0.0001 |

OSCs specifically used for charge transportations are divided into either hole or electron transportation in unipolar devices. Historically acenes like tetracene and pentacene have been promising materials for charge transport. They have excellent intermolecular interactions due to their extended conjugated systems and propensity to form highly crystalline layers. Additionally, they have high charge mobility. Notably, materials such as rubrene and tetracene have seen widespread use.³ Tetracene in fact was the first OFET discovered with light emitting capabilities in 2003 by Hepp et al.⁶

A p-type charge transport material benzothieno[3,2-b][1]benzothiophene (BTBT) and its derivatives are among the most promising materials for OLETs. Due to their unique macromolecular arrangements and fused benzothiophene cores, they show strong orbital coupling between adjacent molecules. When equipped with long alkyl chains, BTBTs form layers where charge transport occurs primarily perpendicular to the molecules π -system through a hopping mechanism. Research is placed on BTBTs because they are transparent in the visible spectral range, they have notably high hole mobility and they are able to used in OLETs at low voltages (<10V).³

For n-type charge transport materials there are far fewer materials than p-type materials. This makes the development of innovative and novel electron-transporting materials highly advantageous because for many LET devices balanced charge injection is crucial. Common n-type OSCs utilized in OLETs for electron transport include C₆₀. For LET devices to facilitate electron injection, a variety of materials with good electron injection such as PFN⁺Bim₄⁻, N-F2-6, NDI and DFH-4T.³

For the light emitting layer, fluorescent materials are the most commonly used in OLETs. These include polyfluorene and phenylene-vinylene that are based on polymers, mainly used in p-channel LETs. Polyfluorene-based polymers are distinctive due to their ability to be used in ambipolar nature as well as high PLQY. Additionally, it is possible to modify them chemically to emit light across the entire visible spectrum. Phenylene-vinylene-based conjugated polymers on the other hand were the first materials used in solution-based LETs. Notable derivatives include OC₁C₁₀-PPV and Super-Yellow.³

Similar to n channel charge transport materials n-channel light emitters have been less frequently reported, primarily due to limited availability of high electron mobility materials that are non-reactive in the presence of moisture or oxygen. Recently, perylene diamide (PDI-C13) is the first n-type LET material capable of operating in air that has been tested. Unfortunately the performance was poor with maximum external quantum efficiency (EQE) of 0.0001 % and brightness of 42 cd m⁻².³

2.3.3 Electrodes

There is a wide range of materials available for electrodes, typically metals deposited in vacuum onto the device. It's crucial to consider that while metals make electron injection easy, many are prone to oxidations and this is especially true for low work function metals like aluminium or magnesium. Alternatively, metal oxides like ITO, ZnO and MoO_x have been employed as stable electron injection electrodes in ambipolar OLETs. In addition, gold and silver have also been used. Of these ITO and gold are the most used. Additionally, with careful adjustment of thickness and refraction index, semi-transparent electrode can be achieved.^{1,3}

Usually, one of the electrodes is a low work function metal and the other is a high work function metal. The reason for this is that employing the same metal for electron and hole injections unavoidably introduces misalignment between their energy levels, causing significant injections barriers and diminishing performance in ambipolar devices. It is also important to

understand that to enhance injection properties, the electronic characteristics of the metal electrode must align with those of the organic semiconductor.^{1,3}

An alternative method, to use the same metal in both electrodes, involves adjusting the metal work function ϕ by introducing dipolar molecules with aligned dipole moments at the interface. A self-assembled monolayer (SAM), which is based on thiols, can be deposited on the metal surface before depositing the OSC to achieve this. Molecules such as Alkanethiols and perfluorinated alkanethiols are commonly used. They form an uniform and ordered SAM on the electrode surfaces to regulate metal ϕ . Due to their opposing electric dipole moments associated with molecules and the Au-S bond at the interface, the work function of the gold can be altered in both directions. Therefore, a potential approach to decrease contact resistance in OLETs using gold electrode for electron and hole injection is to functionalize the drain and source bottom contacts with distinct SAMs.^{1,3}

2.4 Types of OLETs

2.4.1 Single-layer OLETs

As the name states this type of OLET consist of a single OSC material that acts with dual purpose. It handles both charge transportation and light emission. These devices represent the first generations of LETs and utilized a diverse range of material classes, including single crystals, evaporated small organic molecules as well as solution processed polymers. A significant limitation of these first-generation LETs was that they had either good optical or good electrical characteristics but not both, which hindered their EQE and mobility.³

Most single-layer OLETs tend to exhibit only unipolar conduction, either electrons or holes. However, in theory, pure OSCs should support the transport of both hole and electron equally. This means that they should be ambipolar materials. However due to a lack of materials with electroluminescent capabilities as well as strong ambipolar mobility, various device architectures must be employed to achieve high ambipolar transport in OLETs.¹

Rost et al. initially employed a method that involved combining two unipolar materials that have complementary transport properties: α -5T for p-type and P13 for n-type. In these device configurations, the formation of excitons and charge transport are competitive processes. This is so because the n-type and p-type transport materials have a dispersed interface in between. This extensive interface enhances the likelihood of exciton recombination. However, efficient

charge transport requires percolative paths for charge hopping, and the phase interface can act as a physical barrier. Furthermore, the used materials must have compatible highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) levels to enable exciton formation as well as recombination in the material with the smaller energy gap.^{1,7}

2.4.2 Multi-layer OLETs

To address the trade-off between the optical and electrical characteristics in single-layer devices that use a single active organic material, a second generation of LETs was developed featuring either two or more OSC films. This enabled the separation of the emission and charge transport functions into distinct layers. This allowed individual optimizations of the optical and electrical properties of the subsequent OLETs. However, this separation of the layers sacrifices the structural simplicity of single-layer OLETs. These device structures are built by sequentially depositing different active layers vertically onto the substrate. An interface that is continuous as well as has compatible properties is essential, as the condition of the interface significantly affects the luminescent and electrical characteristics of the OLETs. However, this device architecture loses the ability to control photon losses and exciton quenching, as light emission occurs solely in the unipolar regime.^{1,3,8}

Recently, multilayers have replaced single-layer and bilayer organic structures. In such multilayers, e.g., in a trilayer structure, an emission layer is placed. Table 2 showcases some of these multilayer structures and their performances. Trilayer OLET devices have demonstrated EQE values up to 5%, surpassing the 2.2% efficiency of organic light-emitting diodes (OLEDs) with identical emission layers and optimized transport layers. This enhanced EQE is due to the trilayer configuration's ability to effectively mitigate key electroluminescence loss mechanisms. Nonetheless, the performance of the device can vary depending on which of the p-type or n-type layers is positioned closer to the top electrodes. From an engineering standpoint, it's significant that the device's structure can be inverted, allowing semiconductor type interface or interface with a dielectric layer. This flexibility provides greater freedom in designing the device architecture to optimize performance, considering the processing requirements and physical properties of the materials used in the active region.^{1,3}

Table 2. Summary of Multilayer OLETs and their performances. Reproduced from [3] with permission from Wiley.

| Multilayer LETs | | | | | | |
|------------------------------|---|---|---|----------------|---|-----------------------------|
| Device layout | Materials | μ_{hole} [cm ² V ⁻¹ s ⁻¹] | μ_{electron} [cm ² V ⁻¹ s ⁻¹] | ON/OFF ratio | Max power [W] or max luminance [cd m ⁻²] | EQE [%] at max luminance |
| Two layers (planar) | DPP-DTT/Super Yellow | 0.1 | 0.08 | $\approx 10^2$ | 1000 cd m ⁻² | 2.1 |
| Three layers (non-planar) | PBTTT/SPB-02T/DFH-4T | 0.1 | 0.004 | $\approx 10^5$ | 820 cd m ⁻² | 0.05 |
| | PBTTT/SPR-001/DFH-4T | 0.1 | 0.0034 | $\approx 10^5$ | 750 cd m ⁻² | 0.06 |
| | PBTTT/Super Yellow | 0.12 | 0.003 | $\approx 10^5$ | 2100 cd m ⁻² | 0.06 |
| Three layers (planar) | PBTTT/MEH-PPV/PFN ⁺ BIm ⁴⁻ | 0.14 | – | $\approx 10^7$ | 112 cd m ⁻² | ≈ 0.001 |
| | PBTTT/PFO/PFN ⁺ BIm ⁴⁻ | 0.16 | – | $\approx 10^7$ | 137 cd m ⁻² | ≈ 0.001 |
| | PBTTT/Super Yellow/PFN ⁺ BIm ⁴⁻ | 0.1 | – | $\approx 10^7$ | 647 cd m ⁻² | ≈ 0.001 |
| Three layers (planar) | PBTTT/Super Yellow/NDI | 0.05 | 0.004 | – | 180 cd m ⁻² | 0.0008 |
| Three layers (planar) | C8-BTBT/Ir(piq) ₃ :TCTA/N-F2-6 | 0.42 | 0.0077 | $\approx 10^3$ | 17.1 μ W | 3.3 |
| Three layers (planar) | DH-4T/Alq ₃ :DCM/DFH-4T | 0.01 | 0.01 | $\approx 10^3$ | – | – |
| Two layers (planar) | PBTT/ADS077RE | 0.02 | 3×10^{-7} | $\approx 10^4$ | 30 cd m ⁻² | 0.005 |
| Two layers (planar) | DPP-DTT/Super Yellow | 0.5 | 0.2 | $\approx 10^3$ | 900 cd m ⁻² | 0.25 |
| | | | | | 850 cd m ⁻² | 0.09 |
| Two layers (non-planar) | PBTTT/Blue dendrimer | 0.014 | – | $\approx 10^4$ | 650 cd m ⁻² | 2.1 |
| Two layers (non-planar) | DPP-DTT/Super Yellow | 7.6 | – | $\approx 10^6$ | 29000 cd m ⁻² | 0.4 |
| Two layers (non-planar) | DPP-DTT/PCAN | 4.8 | – | $\approx 10^5$ | 9600 cd m ⁻² | 0.7 |
| | | | | | 220 cd m ⁻² | 0.012 |
| Two layers (non-planar) | C ₆₀ /Rubrene | – | 0.6 | $\approx 10^7$ | 220 cd m ⁻² | 0.012 |
| Two layers (non-planar) | C ₈ -BTBT/4CzIPN | 0.2 | – | $\approx 10^6$ | 60 cd m ⁻² | 0.034 |
| Five layers (non-planar) | Pentacene/TCTA/HAT-CN/ TCTA:B3PYMPM/B3PYMPM | 0.11 | – | $\approx 10^4$ | 1890 cd m ⁻² | 3.76 |
| | | 0.26 | – | $\approx 10^4$ | 1116 cd m ⁻² | 0.93 |
| | Pentacene/m-MTDAT/ HAT-CN/m-MTDAT:OXD-7/OXD-7 | | | | | |

2.4.3 Single crystal OLETs

The advent of single crystal OFETs has increased the performance, especially in mobility. Single crystals are highly valuable for fundamental research aimed at understanding carrier transport, recombination and light emission due to their perfect molecular arrangement and minimal defects. Although they are not practical for some device applications, single crystal based OLETs offer an excellent platform for exploring intrinsic characteristics and structure-property relationships. For instance, employing these materials for analysis simplifies examining the impact of defects and impurities. Because the molecules have strong π - π interaction, it necessitates specialized techniques to grow single crystals of organic semiconductor materials for field-effect devices. One method involves using a monolithic single crystal, which can be obtained as a free-standing thin film and then laminated onto a device substrate or grown in situ directly on the substrate. The quality and optoelectronic properties of the deposited crystal can be improved even more if the substrates are treated with

different species of SAMs, such as 1,1,1,3,3-hexamethyldisilazane (HMDS), phenyltrichlorosilane (PTS), and octadecyltrichlorosilane (OTS).^{1,3}

An important thing to know about single crystal OLETs is that they often require a low-work-function metal such as magnesium (Mg) or calcium (Ca) as electrodes for effective electron injection. Another noteworthy thing is that, compared to OLETs based on polycrystalline thin films, the area of emission in single crystal OLETs tends to be more nonuniform. This inhomogeneity can be attributed to challenges with the lamination of single crystal onto the substrate and less uniform distributions of charge carriers.^{1,3}

Pentacene, rubrene and tetracene single crystals have been utilized in organic FETs to achieve high carrier mobility. However, they are not suitable for high-efficiency OLETs, necessitating the development of novel molecules with high photoluminescence efficiency. These semiconductors can be categorized into three classes: silylacenes, phenylenevinylenes and thiophene/phenylene co-oligomers.^{1,3}

2.4.4 Novel concepts

In addition to the previously mentioned OLET types, there are some that are still in early stages of experimentations. One of these is carbon nanotube OLETs. Some of these have been developed, one example being developed by Misewich et al. They developed a single walled carbon nanotube (SWCNT) OLETs, marking the first instance of near-infrared light emission from SWCNT, that was electrically induced. However, the light emission was very little, even with the high carrier mobility in these devices. To date, OLETs based on carbon nanotubes have not reached the desired efficiency and spectral control due to their low efficiency in photoluminescence and variability in diameter, which affects their emission wavelengths.³

Another of these novel concepts are vertically stacked OLETs. Lateral-type OLETs have received most of the focus. Nevertheless, such devices exhibit high driving voltages due to their small aperture ratio, low carrier mobility and relatively low luminance efficiency. One promising approach involves inserting gate electrodes of patterned grid inside the hole transport layer. Similar to OLEDs, these devices can operate at relatively low voltages while handling high current. Examples of vertical OLETs include static induction organic light emitting transistors (SIT-OLETs) and metal-insulator-semiconductor organic light emitting transistors (MIS-OLETs).^{2,3}

As discussed, most efforts in the development of OLETs have centred on material and device structure. Significant advancements have been made in the areas. Nonetheless, the OSCs complex synthesis and the intricate structure of the device often conflict with the original goal of OLETs, which aim to achieve highly integrated yet simplified organic electronics with both electrical switching capabilities and light emitting. To address these challenges, OLETs using alternative current (AC) instead of conventional direct current (DC) have been developed. This innovation removes the need to alter the device structure so that effective injection of holes and electrons into the active layer is possible. The luminous intensity of these devices can be controlled by adjusting the AC voltage's frequency.^{2,3}

2.5 Modelling and simulation

When designing a device, it's important to understand how different variables can affect the device. This is where simulation becomes vital. By adjusting various properties simulation allows flexibility in engineering material parameters. In the case of OLETs, the important design parameters are drive-current, threshold voltage, hole- and electron mobility and on/off ratio. Moreover, simulation can help to refine measurements and fine-tune material thicknesses to optimize the performance of the device before experimental realization. During simulation, general organic models, like singlet, Langevin recombination or Poole-Frenkel mobility, can be added to allow the simulation to be more accurate. These added models address transport and recombination mechanisms within the OSC and the radiative rate for luminescence.^{9,10}

For OLETs, the best simulation software is the Silvaco Atlas 2-D device simulator. It is the current state of the art for semiconductor process and device simulation. It is also used widely in different microelectronics manufacturing industries.^{9,10}

3 Fabrication/manufacturing

The deposition technique chosen during fabrication significantly impacts the organic transistors performance, even when using the same set of materials. Organic materials enable the fabrication of circuits and transistors at temperature up to 120 °C, thereby significantly reducing the cost of manufacturing. Figure 5 illustrates the fabrication flow of a BG-TC structure. The process begins with selecting a substrate, which can for example be silicon, aluminium, glass or plastic.¹¹

A dielectric layer of SiO₂ is typically manufactured by thermally oxidizing silicon at high temperature in an oxidizing environment. Alternatively dielectric materials such as Al₂O₃ can be deposited by atomic layer deposition, while solution processing techniques can be used to deposit the insulating layers of organic materials, the gate as well as flexible substrates, if they are used.¹¹ The active layer can be formed through a few different methods that will be discussed later.

Due to their low solubility in organic solvents pentacene, oligothiophenes as well as other small molecule semiconductors are usually deposited via vacuum deposition. Conversely, conducting polymers like P3HT and polythiophene, can be deposited through spin coating because of their solubility in solvents like toluene and chloroform. A more detailed description of these techniques are provided in the following subsections.¹¹

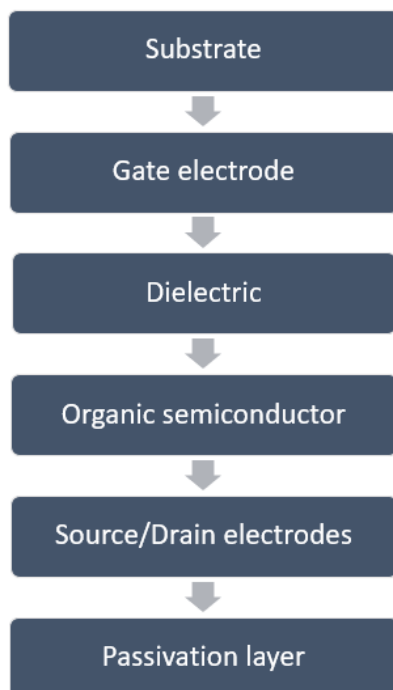


Figure 5. Fabrication process order of a single layer OLET.

3.1 Processes

3.1.1 Solution processed

Solution processable organic materials offer significant advantages for creating large-area electronic circuits at relatively low temperature, which in turn reduces cost. Coating methods for these materials fall into two main categories: direct deposition growth on the substrate and liquid coating techniques. In direct deposition, the material is grown directly on the substrate. In liquid coating, the material is applied in a solvent, and further processing steps are needed to evaporate the solvent and obtain the desired solid phase.^{11,12}

Direct growth methods encompass techniques like electrochemical and electroless chemical bath depositions (CBD). In CBD, controlled reactions and precipitations of reagents in a solution lead to nucleation and film growth on the surface of the substrate immersed in the solution bath. A significant disadvantage of CBD is the substantial solution waste that is generated during the process.^{11,12}

Spin coating is widely used for small-scale processing, because of its high reproducibility and simplicity. In this process, the substrate is held in place by a vacuum chuck on the spin-coater, and a surplus of solutions is put onto its surface. The substrate is then rapidly spun, commonly at several thousand RPM, causing the solutions to spread outward due to centrifugal force. This leaves behind a uniform, thin film after the excess solutions is spun off and the solvent evaporated. In contrast, dip-coating involves immersing a substrate in a solution and then, withdrawing it, which entrains a layer of solutions on the substrate. This can be done either in batches or through a continuous roll-to-roll process. Although dip-coating covers sides of the substrate, there are scalable methods designed to coat just one side. These techniques involve applying a coating to the substrate which is then spread, levelled and thinned using a blade or a rod.^{11,12}

Spray-coating is another technique worth mentioning. It offers the advantage of being a non-contact method suitable for covering large areas. Spray-coating can be used both for direct film growth as well as liquid coating. Typically, the process involves creating an atomized solution through either pneumatic or ultrasonic means, which is then transported to the substrate using a carrier gas.^{11,12}

Direct-write methods such as aerosol jet imprinting and inkjet printing are promising options for material deposition. These techniques provide multiple benefits, which include non-contact

processing as well as the capability to deposit multilayer structures without the use of photolithography, making them suitable for delicate thin-film substrates. Additionally, maximizing material utilization, drop-on-demand (DOD) delivery offers an environmentally- and cost-friendly solution compared to screen printing, which produces waste.^{11,12}

3.1.2 Vacuum evaporation

Vacuum evaporation is a technique that yields semiconductor films with excellent properties in charge carrier transport. It is mainly used for small molecule organic as well as inorganic materials, as the polymers used for conducting tend to decompose or break at the high temperature involved. It has also been used to deposit single crystals. This technique can be divided into thermal evaporation and electron beam evaporation, based on how the material is transported onto the substrate. In thermal evaporation, an electric filament is used to heat the material, whereas in electron beam evaporation, the material is bombarded with a high-energy electron beam to heat it up.¹¹

Electron beam evaporation technique produces films with greater density than those from thermal evaporation because it has accurate control over the rate of evaporation. This method also allows several different materials to be deposited when using a multi-crucible electron beam gun. However, this also requires that the vacuum is not broken. Doing it this way enhances material adhesion to the substrate and improves interlayer interfacing. Unlike thermal evaporation, which heats the entire crucible and generates more contaminants, electron beam evaporation only heats the material, reducing contamination. However, this technique requires an electron processing unit that is expensive and complex. This makes it more difficult to scale when comparing it to thermal evaporation.¹¹

Vacuum deposition techniques excel at producing highly ordered films with precise thicknesses. However, they require a highly sophisticated vacuum chamber to ensure proper charge carrier flow. Additionally, the need for very high deposition temperatures makes this method unsuitable for flexible and low-cost devices.¹¹

3.1.3 Physical vapor deposition

Physical vapor deposition (PVD) encompasses a range of deposition techniques meant for thin-films, in which solid materials are vaporized in vacuum before being deposited on substrates as either alloy compositions or pure materials. This process involves evaporating or sputtering a

material to produce a beam or gaseous plume, which then deposits a film onto the substrate. PVD techniques are renowned for creating highly durable coatings that are resistant to scratching and corrosion, making them useful for producing a variety of devices including semiconductors.¹³

The advantages of PVD are numerous. Moreover, PVD is an environmentally friendly technique that significantly reduces the use and disposal of toxic substances compared to other “wet” processes which rely on chemical reactions and fluid precursors. However, PVD has potential drawbacks, primarily related to cost. The initial investment for PVD equipment can be higher than for other deposition methods, and cost can differ among different PVD techniques. Despite this, the long-term benefits of durability and environmental friendliness often outweigh the initial expenses.¹³

Sputtering is another PVD technique, which is a process where high-energy particles are bombarded at the target material, which then deposit onto a substrate, like glass or silicon wafer. In this method, the substrates that are being coated are placed in a vacuum which is filled with some inert gas, typically argon. The target material is then applied with a negative electric charge, which causes the plasma in the chamber to glow. Through collisions with the argon gas atoms, atoms from the target are “sputtered off”. The argon atoms then transport these particles across the vacuum chamber so that they can be deposited on the substrate.¹³

3.1.4 Neutral cluster beam deposition

Neutral cluster beam deposition (NCBD), a novel but less common deposition technique, offers promising advantages. This method employs a cluster beam with translational kinetic energy and high directionality, achieved through the adiabatic expansion of organic vapor molecules into a high vacuum. Due to the weakly bonded nature of the neutral organic clusters, their collision with a substrate such as SiO₂ facilitates easy dissociation into individual molecules. This process enhances active surface migration, which results in organic thin films that have major improvements in surface morphology, room-temperature substrate deposition, packing density and crystalline quality. These benefits are not attainable with conventional vapor deposition methods.¹⁴

Choi and colleagues were one of the first to introduce the NCBD method to fabricate bilayer ambipolar OLETs. They sequentially deposited α,ω -dihexylsexithiophene (DH6T) and P13,

achieving notable field-effect mobilities, electroluminescence and stable operation without stress under ambient conditions.¹⁵

3.2 Encapsulation

Organic light emitting devices including OLETs and OLEDs, suffer from degradation when exposed to humidity or oxygen. While encapsulating these devices between glass plates is an effective method to protect them, it compromises their flexibility and mechanical durability, making it unsuitable for large-scale, cost-effective production. The issue of permeation through single inorganic films can be linked to pinholes as well as defects. To address this, researchers have explored passivation techniques that employ thin composite polymeric film structures with single and multilayer to enhance the longevity and stability of flexible devices. The most effective method for achieving ultra-high barrier properties involves alternating layers of organic and inorganic materials, where inorganic barriers are interspersed with polymeric buffers, significantly reducing the occurrence of pinholes.¹⁶

While these multilayer structures meet the industry's lifetime requirements of over 10 000 hours, their fabrication using vacuum deposition methods is both complex and costly. Achieving fully printed "plastic" electronics requires development of manufacturing methods where low-cost encapsulation barriers can be applied through solutions processing techniques.¹⁶

The permeability of encapsulated membrane to oxygen and moisture is qualified by the oxygen transmission rate (OTR) and the water vapor transmission rate (WVTR). For organic electronic devices to achieve lifetimes exceeding 10 000 hours, the OTR and WVTR values must be six to eight orders of magnitude lower when compared to polymer films that are commercially available. To measure both OTR and WVTR, a calcium optical thin film transmission test can be used. The test relies on corrosion of thin calcium films. In this test, thin calcium films are deposited on the chosen substrate and then transparent barrier layers are placed around to encapsulate the test device. During the test the reflective calcium turns into calcium salts when it comes into contact with the permeated water and oxygen, increasing the transmission percentage from 0% to 100%.¹⁶

4 Characterization

4.1 Testing

Various characterization techniques provide valuable insight into current problems. Local microscopy methods, like scanning Kelvin microscopy, scanning near-field optical microscopy as well as confocal microscopy, can resolve potential profiles and emission within the channel, creating detailed maps of the dielectric/organic interface. Multiphoton time-resolved spectroscopy, including electric-field-induced second-harmonic generation, is instrumental in elucidating electric- as well as charge-field-induced quenching phenomena in operating OLETs.¹

For the testing of optical properties, it requires a photometric bench. It is a sophisticated setup for optical testing which is often equipped with telescopes that are used to align the light source with the optical axis as well as multiple aperture screen to prevent stray light from entering the photodetector. Photometers or even standard lamps are used for reference. Lamps that have standard luminous intensity, are calibrated in a single horizontal direction, produce candela, which is the unit of luminous intensity. This kind of protocol is used in brightness measurement in extended surface light sources like OLETs. Luminance meters and spectroradiometers are particularly prevalent in both R&D and academic laboratories.¹

Some of the approach that researchers have tested for OLET devices include Jin et al. measuring current-voltage characteristics using a source meter, a KEITHLEY-2400, 237 and measuring radiance with a Newport 1830-C photodiode. These measurements were also done in N₂ atmosphere. In another approach used by Sarjidan et al., they measured current-voltage-luminance characteristics in one, using a Konica Minolta CS-200 chroma meter. Also, Capelli et al. used a Nikon Eclipse 2000-E microscope to obtain optical micrographs of the recombination region as well as device channel.¹⁷⁻¹⁹

4.2 Optical properties

4.2.1 External quantum efficiency (EQE)

EQE is a crucial metric for evaluating the light generation efficiency of any light-emitting device. This parameter quantifies how effectively the device converts electrical current into emitted light. EQE is defined as the ratio of the photon flux per unit area detected outside the device to the carrier flux per unit area ζ injected into the device:

$$\eta_{ext} = \zeta \gamma_{PL}^{\Phi} \chi_{out}^{\sigma}$$

Here, γ represents the ratio of exciton formation events to the number of charges flowing in the external circuit. σ_{out} is the light outcoupling efficiency from the device into open space, χ is the spin multiplicity of the radiatively recombining excitons, and Φ_{PL} is the luminescence quantum yield of the exciton formation layer. Electron-hole capture plays a pivotal role in the optoelectronic performance organic light-emitting. For efficient capture within the micrometre-wide in-plane recombination volume typical of OLETs, maintaining a sufficiently high charge density is essential to ensure that oppositely charged carriers can meet within the collisional capture radius.¹

In single-layer ambipolar OLETs, it's anticipated that all carriers will recombine because charges are unable to traverse several micrometers in the accumulation layer of the opposite charge without recombining. When central region of the channel emits light, far enough from the drain and source edges to avoid the contact interface, the EQE of the ambipolar transistor remains steady. This steadiness is determined solely by the light outcoupling efficiency, the radiative yield of the formed excitons as well as the singlet/triplet ratio. Factors like the hole and electron mobility ratio or applied voltage do not affect it. Generally, γ is assumed as 1, though it is closely related to the balance between mobility of holes and electrons.¹

The fraction of radiative species in the emission layer is significantly influenced by the singlet-triplets ratio. For instance, in fluorescent materials, only singlet states emit light, meaning that triplet states do not affect electroluminescence. Quantum-statistical principles dictate that charge recombination produces only 25% singlet excitons, a proportion that can be further diminished by static quenching mechanisms. The mechanisms typically involve charge trapping at the dielectric/semiconductor interface as well as quenching induces by electrodes. The luminescence quantum yield, representing the part of excitons which relax radiatively, is determined by the material's intrinsic properties and is further decreased by interactions with quenching species.¹

Dynamic quenching includes processes such as exciton scattering with other excitons, defects and chemical impurities, free charge carriers (polarons), in addition to excitons dissociation into electrons and holes. Ideally, ambipolar OLETs should minimize or eliminate electrode-induced quenching as well as exciton-polaron scattering.¹

Another significant factor to consider is the interaction between excitons and carriers. In this process, the excitation energy is transferred to a charged molecule from the excited neutral molecule nonradiatively through Förster transfer, which is a dipole–dipole interaction. Determining the precise current density in a single-layer light-emitting transistor presents several challenges. It is difficult to ascertain the duration for which electrons and holes stay at the interface within the recombination zone when compared to their respective accumulation regions, or the extent to which they diffuse from the interface into the bulk. This diffusion and confinement can vary depending on the applied voltage conditions. Despite these uncertainties, an estimation of the current density in light-emitting transistors can be achieved by considering the flow of current through an area defined by the channel width as well as the emission zone's height. However, this estimation does not factor in the emission zone width in OLETs, which ranges from 2 to 4 micrometers, indicating that charge recombination in an OLET is less spatially confined than in an OLED.¹

4.2.2 Brightness

Brightness is one of the most important characteristics of OLETs for obvious reasons. However, light emission performance and the brightness reported for OLETs have been relatively low. This can be attributed primarily to the organic materials used so far in OLETs, because they either have high photoluminescence with low carrier mobility, like the amorphous organic semiconductors utilized in OLEDs, or weak photoluminescence with high mobility, which are seen in crystalline materials. For high performance to be achieved, materials need to facilitate ambipolar carrier injection and transport from source-drain electrodes. They also need to exhibit high photoluminescence efficiency in thin film as well as maintain carrier transport that is relatively good. Achieving a balance among these three factors within a single-layer OLET is a significant challenge in synthesis and fabrication. While ambipolar OLETs have achieved some success, high efficiency is generally observed only at the lowest current levels, where the light emission is quite dim.¹

When addressing brightness, it's crucial to consider the experimental setup and protocol to ensure accurate and effective luminance measurements. According to applied photometry guidelines, the luminance of a point source emitting within an elemental solid angle $d\Omega_s$ is defined as the radiant flux $d\Phi$ per unit solid angle and per unit area perpendicular to a specific direction, i.e.,

$$L = \frac{d^2\Phi}{d\Omega_S dA_S \cos\theta}$$

here dA_S represents the elemental area containing the point in question, θ is the angle between the normal to the elemental area and the specified direction and $d\Omega_S$ encompasses the given directions.¹

This conventional luminance definition applies as long as the emitting source is able to be viewed as point-like. In practical photometric and radiometric scenarios, which often involve extended sources like those in organic optoelectronic devices, it's typically assumed that these sources are approximated as a collection of distributed point sources which are uniformly and identical. A source is considered point-like if its lateral dimensions are much smaller than the square of the distance to the observer. An ideal point-like source radiates isotropically, emitting the same amount of flux uniformly in all directions. In OLETs, despite the devices inherently planar geometry and anisotropy, this condition is often met due to the micrometric length of the active channel.¹

When calculations include the entire device area, OLETs luminance values are often lowered by an order of magnitude, encompassing both the electrodes and the non-emitting parts of the channel. To mitigate this, the proportion of illuminated to dark areas can be improved by designing devices with shorter channel lengths and smaller electrode pads. Brightness is influenced by both the emission efficiency as well as drain current, with the peak brightness occurring at the boundary of the ambipolar regime. Here, the recombination zone starts to separate from the edge of the electrode. In addition, the EQE approaches its maximum within the ambipolar regime. Luminance falls to roughly half of its peak value at the lowest current point in the middle of this regime. However, by slightly adjusting the operating conditions away from this minimum current point, both high efficiency and bright emission simultaneously.¹

4.3 Electrical properties

4.3.1 Recombination location

A unique feature of OLETs and large field effect transistors (FETs) is that they are bidimensional unlike diodes. This means that they have two different perpendicularly oriented electric fields which govern them. These originate from the potential difference between the gate electrode and the source electrode which is called V_{gs} . The other comes from the difference

in potential between the drain electrode and the source electrode V_{ds} . The source electrode is usually grounded. It is also important to understand that all of the induced charges are not mobile. The reason for this is that there are deep traps that require filling before additional charges can be mobile. This voltage is called the threshold voltage V_t . This means that the effective gate voltage is $V_{gs} - V_t$.^{1,20}

In the context of the graduate channel approximation, it is possible to deduce a straightforward expression for the ambipolar regime. Usually, an infinitely high recombination rate for both electrons and holes implies that all injected carriers will recombine. Consequently, the source-drain current equals the current carried by both holes and electrons in each channel. With these assumptions the source-drain current for ambipolar regime can be calculated by the following:

$$|I_{ds}| = \frac{WC_i}{2L} \{ \mu_e (V_{gs} - V_{t,e})^2 + \mu_h (V_{ds} - (V_{gs} - V_{t,h}))^2 \}$$

For the unipolar regime the source-drain current can be calculated followingly:

$$|I_{ds}| = \frac{W}{2L} \mu_e C_i (V_{gs} - V_{t,e})^2$$

where C_i is the capacitance per unit area of the gate dielectric, μ_e and μ_h are the mobilities of electrons and holes in the dielectric material, $V_{t,e}$ and $V_{t,h}$ are the threshold voltages for electrons and holes. For unipolar function it is important to remember that depending on if the transistor is either n- or p-type the mobility and threshold voltage change to the corresponding values. The position of the recombination zone x_0 can be calculated by the following:

$$x_0 = \frac{L(V_{gs} - V_{t,e})^2}{(V_{gs} - V_{t,e})^2 + \frac{\mu_h}{\mu_e} (V_{ds} - (V_{gs} - V_{t,h}))^2}$$

where x_0 affirms the location of the recombination zone. Consequently, the area where light emission occurs, is contingent upon the applied voltages and the relative values of hole and electrons mobilities.^{1,20}

4.3.2 Recombination rate and width of recombination zone

Little investigation has been done for the recombination zones width. In theoretical studies, the bimolecular rate of recombination is often assumed to be infinite, resulting in a recombination width of zero. When a high recombination rate is imposed, such that holes and electrons are not

able to bypass each other without recombining, it is possible to solve the device equation analytically. In this scenario, recombination occurs at a single point where the electric field is at its peak and the potential of the effective gate is zero. Considering the common presumption that holes and electrons move along the channel independently, modeling the ambipolar OLET as parallel unipolar p-type and n-type transistors in saturation, can be considered to have limited physical significance.^{1,21}

To address the inadequacy of determining the recombination rate using the Langevin expression, it is essential to explore its limitations and propose alternative. The discrepancy between experimental outcomes and theoretical predictions in OLETs might stem from the quasi-two-dimensional transport characteristics of these devices. Through various techniques it was demonstrated that, in the context of two-dimensional transport the rate constant shows only a weak dependence on charge density.^{1,21}

To better define vertical dimension of the recombination zone of from the dielectric interface, an exponential decay function was utilized. It increases with distance from the insulator/semiconductor interface. This approach helps to describe the spatial profiles of holes and electrons more accurately. Thus, the recombination rate can be articulated as follows:

$$\gamma = \frac{e(\mu_n + \mu_p)}{2\varepsilon_0\varepsilon_r\gamma_0} = \frac{e(\mu_n + \mu_p)G}{2\varepsilon_0}$$

where μ_n and μ_p are the mobilities of their types of transistors, ε_0 is the vacuum permittivity, ε_r is the dielectric constant. The Coulomb attraction between holes and electrons is modulated by a dielectric constant, which screens the interaction. Given the uncertainty in the confinement of charge carriers perpendicular to the semiconductor/insulator interface, the parameter $G = 1/(\varepsilon_r\gamma_0)$ is used to represent the vertical recombination width.^{1,21}

In areas of the channel where both holes and electrons are present, recombination occurs over a length scale determined by:

$$W = \sqrt{\frac{e(\mu_n + \mu_p)}{\gamma C_i}} = \sqrt{\frac{2d}{\varepsilon_r}} \sqrt{\frac{1}{G}}$$

where ε and t represent the dielectric constant and the thickness of the gate insulator, respectively. In a simplified model, the assumption that $G \rightarrow \infty$ leads to $W \rightarrow 0$. Generally, G

is considered a functional parameter meant to account for the decay in hole and electron concentration profiles when the distance from dielectric surface increases.^{1,21}

Kemerink et al. proposed a theoretical approach based on the conventional Langevin mechanism, where carrier densities within the recombination zone are solely determined by the recombination process. They introduced a recombination rate based on the Langevin bimolecular recombination rate constant and then computed carrier densities. The recombination width W was then defined as the distance at which the recombination rate decreases to $1/e$ of its peak value, discovering that:

$$W = \sqrt{4.34d\delta}$$

where d represents the thickness of the gate insulator and δ denotes the accumulation layers thickness. Both methods yield comparable outcomes, with the recombination width being affected by the accumulation layer's thickness and the dielectric properties. They both indicate that the recombination zone in a single-layer OLET can extend upto 500 nm at most.^{1,21}

5 Applications

5.1 Displays

OLETs present an innovative approach to display pixel design by combining the switching capability of FETs and the light emitting function of OLEDs in a single device. Thin integrated pixel design simplifies the circuitry typically needed for conventional active-matrix OLED (AMOLED) pixels, offering potential benefits in terms of higher transparency, reduced costs and easier fabrication. Moreover, controlling light emission via gate voltage bias in the OLETs significantly affects the design considerations for the driving circuitry and the selection of backplane technology in active-matrix OLET (AMOLET) displays.^{1,22}

The AMOLET display includes several key components: a driving power supply line ELVDD that is connected to the first electrode (source), and a common power supply line ELVSS which is connected to the second electrode (drain). The gate electrode is managed by a MIM switching element, connected to a scan line. Additionally, a storage capacitor (Cs) bridges the gate electrode and the switching element, with a data line linked to the storage capacitor. The MIM switching element, activated by the scan line, switches the gate electrode on and off according to the scan signal. A data signal is supplied by the data line to the storage capacitor, which retains this signal and delivers it to the gate electrode for each frame.^{1,22}

It is possible to integrate multiple OLETs as subpixels within a single pixel in order to create displays that are more advanced. The incorporation of OLETs enhances uniform light emission in organic electroluminescent displays. This also allows the backplane to be simplified when compared to AMOLED displays. Because OLETs displays are voltage driven, similarly to liquid crystal displays (LCD), it is possible to significantly streamline the driving circuit. Since AM-OLET displays operate like AM-LCD displays, they can leverage TFT technologies, which perform worse but are much cheaper than LTPS. This approach broadens backplanes manufacturing possibilities when using generic TFT technologies.^{1,22}

Production of OLET displays is still in development, however great steps are being taken. An example of this is that Miao et al. were able to create a high-performance white light emitting OLET, with an EQE of 13.9%. The remarkable efficiency of these OLETs is attributed to their light outcoupling efficiency as well as high exciton utilization, alongside reduced quenching. It is anticipated that with a more profound understanding of the operating mechanisms and by optimizing the fabrication of these devices, such as further enhancing light outcoupling

efficiency as well as exciton utilization, achieving balanced electron-hole injection and transport, incorporating superior emissive materials, OLET performance will significantly improve. The achievement of white OLET arrays for full-color displays in the study can be regarded as a major step forward in their development for use in smart display technologies.^{1,22}

5.2 Sensing

Chemical sensors represent a paradigm shift in analytical chemistry, transitioning to specialized, dedicated systems from general analytical systems. These sensors provide real-time chemical information on-site through a two-step process of signal processing and recognition, resulting from the interaction between the sensor and chemicals. In this context, OLETs emerge as an intriguing group of planar optoelectronic devices, where the emission of light stems from an OFET structure. Integrating a photodetector into the planar structure could enhance the geometrical fill factor of the OLET structure in an in-plane detection setup. Furthermore, the inherent electrical switching capability of OLETs enables their arrangement into sensor matrices without requiring additional driving circuitry, making them highly efficient for such applications.^{1,23}

In OLETs, it is possible to alter the spatial position of the light emission zones in the transistor channel by adjusting the gate voltage. This distinctive capability of the planar field-effect architecture can be leveraged to develop innovative detection and excitation schemes for the next-generation optical sensors. This can be done by optimizing the optical integration within the photonic components of a lab-on-a-chip (LOC) system. Additionally, the in-plane light generation, which occurs away from the charge-injecting electrodes and within a micrometer-wide, stripe-like area of emission, offers distinctive photonic advantages inherent to OLETs.^{1,23}

These advantages include: (1) eliminating light couplings optics, (2) enabling greater photonic component integration through monolithic device fabrication onto functional layers and (3) optimizing and simplifying the coupling with microfluidic chips, given that the typical OLET channel length (30–100 μm) aligns well with fluidic microchannels.^{1,23}

Using transistors instead of diodes offers four main advantages. Firstly, it is possible to fabricate them in a top-gate geometry where the substrate already has the drain and source electrodes predeposited, ensuring precise alignment with the microfluidic chip. Secondly, the device construction is simplified because only a single layer of organic semiconductor is needed which is then followed by the gate dielectric/electrode, eliminating the required ITO electrodes as well

as elaborate multilayer structures. Thirdly, the in-plane light generation by the transistors improves optical coupling into waveguiding structures, enhancing performance. Finally, additional transistors can be incorporated to function as amplifiers for the phototransistors or as drivers for the light-emitting transistors.^{1,23}

The concept of sensors is widespread, but its true potential is realized in portable devices that transform laboratory functions into easy-to-use analytical tools. Once optimal performance levels are achieved, sensors utilizing the organic photonic field-effect platform are poised to transform the point-of-care diagnostic industry. These sensors will facilitate the development of diagnostic devices which are portable, featuring highly sensitive, quantitative and multiple detection techniques, all capable of functioning without requiring a specialized desktop reader..^{1,23}

5.3 Challenges/issues

The demand for transparent display technology is significant. This is driven by its potential applications in automobile navigation systems, augmented reality, biomedical head-mounted goggles as well as car windscreen displays. To meet this demand, ultrahigh brightness and highly transparent display pixels are needed, as current AMOLED pixels fall short. A new type of display pixels with transparency is urgently needed.³

The main issue with OLETs is bad light out-coupling from underneath the drain and source contacts. Even in multilayer configurations, achieving the required brightness necessitates high voltages. Furthermore, there is a lack of data on how these devices perform under continual bias stress, making their suitability for working displays uncertain.^{3,8}

The development of emissive organic semiconductors with high-mobility is crucial for improving OLET efficiency. Ideal materials should have moderate charge transport, less EQE roll-off, high PLQY, solution processability, and high operational stability. Although some progress has been made, significant improvements in balanced transport of electrons and holes, charge transportation properties, and increased exciton utilization are still needed.^{3,8,24,25}

Additionally, in-plane architecture of OLETs makes it easier to directly probe the charge injection, current flow, and exciton formation. This architecture also allows for better integration with photonic components, potentially leading to innovative detection and excitation schemes in the optical sensors of next-generation. To achieve practical applications, it is necessary to improve OLET characteristics such as high brightness, high on/off ratio, high

EQE, well-balanced carrier injection, high mobility, low operating voltage as well as tunable emission zones.^{3,8,24,25}

Several challenges remain, including the development of organic semiconducting materials specifically for OLETs, optimization of device fabrication, and addressing stability and performance issues. Efficient strategies for forming single crystals of organic small molecules, improving carrier mobilities, and enhancing diode characteristics are essential. Additionally, more cost-effective and environmentally stable methods for manufacturing these materials are needed.^{3,8,24,25}

5.4 Next development stages

OLETs have seen significant advancements in recent years, leveraging structural solutions and materials from OTFTs as well as OLEDs. However, several key issues must be addressed to realize full potential of OLET technologies and enable its widespread use in display, healthcare, and sensor markets. These issues include reliability, lifetime, power efficiency, and color gamut.^{1,24}

A significant challenge is the development of stable and efficient blue emission, crucial for high-quality display applications. Current research has demonstrated OLETs emitting various colors, including the fundamental red, green, and blue. However, optimizing the color gamut and efficiency, especially for blue emission, remains a significant hurdle. The need to balance pixel resolution, operational stability, and photonic characteristics is paramount.^{1,24}

Power consumption is another critical factor, particularly for mobile applications like e-readers, wearable devices, smartphones, and notebooks. OLETs have the potential to offer lower power consumption than OLEDs, benefiting from their planar electrode arrangement, which avoids cavity effects and reduces light losses at interfaces. Additionally, the wider viewing angle of OLETs, due to their isotropic emission, makes them attractive for various display technologies. Despite these advantages, integrating low-power OLET devices into AMOLED displays presents a manufacturing challenge.^{1,24}

The lifetime and reliability of OLETs are crucial for their commercial viability. Organic-based technologies are sensitive to moisture and oxygen, leading to degradation. The planar structure and lateral charge transport of OLETs, along with the ability to balance hole and electron currents and tune the recombination area, offer a higher degree of control over excitonic and electronic processes. This control can lead to reduced degradation and longer device lifetimes.

Developing a low-cost, flexible, thin-film barrier technology that provides environmental protection is essential for the longevity and manufacturability of OLETs.^{1,24}

Material development is also critical. High mobility emissive organic semiconductors, currently dominated by p-type materials, need to be complemented with n-type and ambipolar materials to improve OLET efficiency. Lessons from OLED research can guide the selection of functional materials, device construction, and optimization of interfacial quality. Enhancing light transport and output through improved fabrication technologies is another area requiring attention.^{1,24}

Finally, OLETs have inherent advantages for photonic devices and circuits, controlling both channel current and electroluminescence. Developing efficient photon paths and coupling mechanisms within OLETs is a challenging yet promising area for advancing display technologies and multifunctional optoelectronic devices. Future breakthroughs are expected in applications like electrically pumped organic lasers and integrated optoelectronic circuits, pushing the boundaries of what OLETs can achieve.^{1,24}

In summary, while OLETs have made significant strides, ongoing efforts are needed to address challenges in color quality, power efficiency, lifetime, material development, and photonic integration to fully utilize their potential in various advanced applications.^{1,24}

6 Conclusion

In conclusion, OLETs emerge as a promising technology at the intersection of display and sensing applications, leveraging their integrated field-effect architecture to combine electroluminescence, electrical switching as well as photon management within organic materials. This unique combination allows for cost-effective, large-scale production on a variety of substrates, including plastic, metal foils, and glass. OLETs operate independently of current density, simplifying driving circuits and positioning them as a viable alternative to traditional OLEDs. Their advantages include enhanced efficiency and longevity of organic light-emitting materials.

The versatility of OLETs is further underscored by their tunable emission colors through molecular engineering, making them suitable for flexible displays and sensors. They offer structural advantages over OLEDs by reducing photon losses and exciton quenching, thanks to their planar field-effect configuration. This configuration also allows for better light guiding, confinement, and extraction, contributing to brighter and more efficient electroluminescence.

Despite ongoing challenges in material selection, fabrication processes, and interface management, continuous advancements in organic semiconductors, dielectric materials, and device architectures are paving the way for improved performance and broader adoption of OLET technology. The potential of OLETs to integrate into sensing platforms, optical communication, and optoelectronic systems highlights their immediate applicability and future promise. Their ability to utilize lower quality TFT backplanes for driving circuits, coupled with their ease of processing and reduced risk of technological hurdles like pin holes and shorts, positions OLETs as a next-generation display technology suitable for both flexible and rigid applications.

Overall, OLETs represent a significant advancement in optoelectronic devices, blending the best attributes of organic field-effect transistors and organic light-emitting diodes. Future research aimed at overcoming current limitations and optimizing material properties will be crucial in realizing the full potential of OLETs in commercial applications, making them a key player in the evolution of display and sensing technologies.

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