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Review article

Advancements in stretchable organic optoelectronic devices and flexible transparent conducting electrodes: Current progress and future prospects

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ABSTRACT

The rapid evolution of flexible optoelectronic devices in consumer markets, such as solar cells, photonic skins, displays, lighting, supercapacitors, and smart windows, has spurred global innovation in the design and development of Stretchable Transparent Conducting Electrode (STCE) materials. These materials, which combine the flexibility of organic materials with the functionality of optoelectronic components, have drawn a lot of attention because of their potential uses in a variety of disciplines, such as medical equipment, wearable electronics, and soft robotics. Recent advancements in material science and device design have significantly improving performance, durability, and functionality of these stretchable organic optoelectronic devices. Furthermore, flexible conducting transparent electrodes play an essential role in a wide range of flexible and transparent electronics, including touch screens, displays, and solar cells. Traditional materials like indium tin oxide (ITO) electrodes, while effective, and constrained by their fragility and high cost. Recent innovations in alternative materials, such as metal mesh, nanowires, conducting polymers and graphene have ushered in a new era of affordable, flexible, and transparent conductive electrodes. Materials like graphene, metal nanowires, metallic grids, metal meshes, and dielectric-metal-dielectric electrodes are explored as potential substitutes for fragile ITO electrodes, thanks to their excellent combination of mechanical flexibility and electrical conductivity. This abstract delves into the opportunities and challenges in the development of flexible and transparent organic optoelectronic devices and flexible conducting transparent electrodes. In this review, we explain the technological advancements of transparent and stretchable electrodes, as well as their applications in organic optoelectronic devices such as organic and perovskite solar cells, OLED, heaters, and supercapacitors. We will specifically examine the basic characteristics, optoelectronic properties, and manufacturing procedures of transparent conducting electrodes. We also discuss the key criteria for evaluating proposals for new research lines in this burgeoning sector.

1. Introduction

The rapid growth of modern stretchable and transparent optoelectronic consumer products including solar energy cells, optoelectronic skins, screens, transistor, supercapacitors, and smart windows has led to the design and development of Stretchable

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transparent conducting electrode (STCE) materials on a worldwide scale. Many electrical and optoelectronic technologies, including touch screens, liquid crystal displays (LCDs), organic light emitting diodes (OLEDs), photovoltaics and transparent heaters, depend on these electrodes in some way. Flexible and transparent optoelectrical devices are a novel class of mechanically stretchable electronics that are gaining popularity and optical transmittance of the devices are thought to be one of the key technologies for the applications of the future generation of electronics. In the last 10 years, the market for touch screens and electronic displays has expanded dramatically. Emerging device technologies also need for new transparent electrode features such mechanical flexibility, high optical transmittance simple production methods, low cost, and light weight [1,2].

Organic optoelectronic devices have an advantage over conventional inorganic electronic devices in that they may be built on transparent and elastic substrates, providing better elastic flexibility and longer effective life under mechanical deformation. In addition to their excellent electrical performance, these devices operate at low temperatures, are easily accessed over a large and affordable area, and may be used to adjust optical properties through molecular engineering. These features make them highly sought-after gadgets. Stretchable organic optoelectronics is a potential technology that may be used to create user-friendly integrated electronic systems containing a variety of functional components, including photovoltaics, light-emitting diodes, photodetectors, and thin-film transistors (TFTs). Studies on optoelectronic devices that may be applied to human skin and tissue have previously suggested that practical biological uses for these devices may exist. For example, patients are released from location-based constraints when their physiological status can be reliably, constantly, and correctly monitored. The retrieved medical data may be immediately sent to licensed specialists for diagnostic evaluation, enabling patients to get real-time at-home self-healthcare without experiencing any disruptions to their regular activities. Therefore, it is expected that both industry and academics will gain from the extraction of biometric data at human-machine interfaces via wearable smart sensing integrated systems [1,3,4].

In Figs. 1 and 2 schematic device configurations and illustrative images of a Thin Film Transistor (TFT), an Organic Light Emitting Diode (OLED), and an Organic Photovoltaics (OPV) respectively First of all, there is a high need for novel varieties of flexible, stretchy, or foldable substrates [5].

The substrates, which must have low atmospheric moisture and oxygen penetrability, high optical transparency, lesser resistivity, lower surface thickness, low surface roughness, and superior bending capability, are a key factor in mechanical flexibility or stretchability. The limitation of transparent conductive electrodes presents the second major obstacle for flexible optoelectronic systems. In this review we focused on the fabrication technique and collection of the data of the reported devices like low sheet resistance and optical transmittance of the compounds used in the HTL and ETL which is shown in Table 1.

2. Organic optoelectronic devices

Organic optoelectronic materials (such as anthracene) have been studied for their optical and electronic properties for nearly a century, with the earliest research being published in the 1910s. The discovery of conducting polymers and electroluminescence in molecular crystals increased interest in such materials in the 1960s and 1970s. However, during the past 30 years, there has been a considerable increase in interest in the field of organic optoelectronics because of significant advancements in material design and purification that have significantly improved the performance of the materials [3].

Over the past few decades, optoelectronic technologies such as light-emitting diodes (LEDs), photovoltaics and laser have been widely used in many areas of modern life, such as consumer electronics, telephony, and solid-state lighting [7]. Because of the unique properties that set organic semiconductors apart from their inorganic counterparts, OSCs have been extensively studied and employed in several electrical devices since their inception. Nearly all organic devices are thin-film multilayer devices, like organic photovoltaics (OPVs) and organic light-emitting diodes (OLEDs), which employ organic layers as the functional layers and metal layers as the electrodes.

Interfaces between organic materials and metal are therefore essential for enhancing device performance [8]. Modern OPV devices have power conversion efficiencies that are more than 10 %, which is now getting close to the efficiency that the industry is proposing as being necessary. Samsung's active-matrix OLED displays for smart phones and LG's 55-inch OLED TV are two examples of commercially available displays that use OLED technology [9].

The neutral mechanical plane, where the stress is reduced, and thickness and modulus optimization are two techniques that are frequently used to increase flexibility. Such flexible electronic goods like Samsung's YOUM flexible screens have already been released

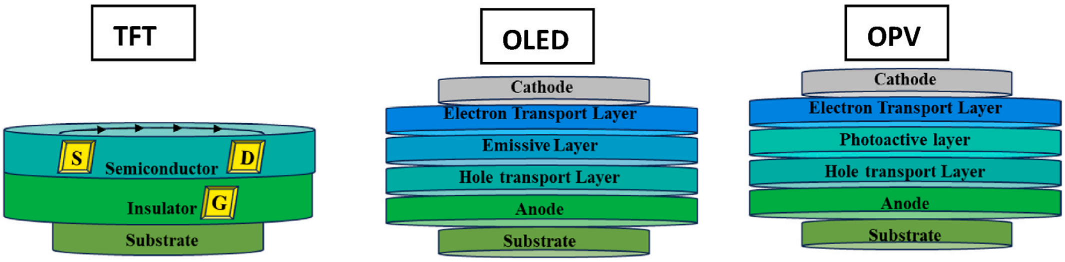

Fig. 1. Schematic device configurations of a Thin Film Transistor (TFT), an Organic Light Emitting Diode (OLED), and an Organic Photovoltaics (OPV) respectively [6].

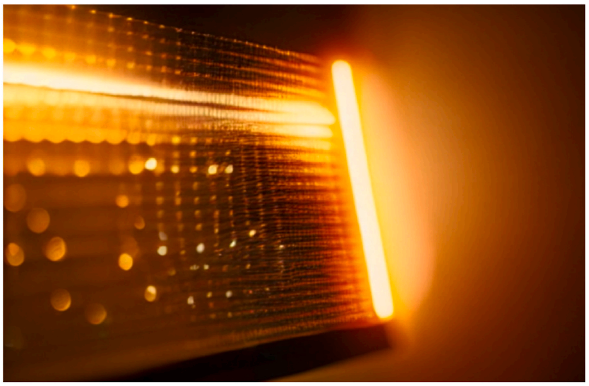

Fig. 2. Illustrative image of Optoelectronic device like OLED, OPV.

and will soon be available for purchase. These gadgets do not qualify as stretchable electronics, while being fascinating and maybe helpful. It doesn't matter how flexible a technology is, it still can't be bent whatever you want. In contrast, a flat sheet of paper cannot be readily extended or freely distorted in any other way without breaking. For instance, a flat sheet of paper may easily bend when folded. A thin sheet of rubber, on the other hand, may be bent, repeatedly stretched, squeezed, and then released without permanent distortion. Therefore, a device must allow for extension, compression, and stretching in addition to bending to be deemed stretchy [10].

In Fig. 3. Shows some commercially available optoelectronic devices like Photodiodes, Solar cells, Optical Fibers etc. The transmittance of the substrate is particularly crucial for organic optoelectronic devices, especially when it comes to concerns with optoelectronic devices and the direction of light incidence and departure. Another crucial optical characteristic is optical haze [11]. TCEs' sheet resistance (R_{sheet}) and optical transmittance at 550 nm (T_{550nm}), which is the wavelength at which human eye sensitivity is at its highest, may be used to characterize and compare their optoelectronic characteristic in general [12]. The low sheet resistance (Rs) of 5–40 Ohm/sq and high optical transmittance (T_{550}) of 90 % at 550 nm of indium tin oxide (ITO) have made it an effective choice for the industry standard TCE. Sadly, due to the high cost of indium, the need for costly vacuum processes, and mechanical brittleness, standard ITO films are not suitable for next-generation optoelectronic applications, such as flexible displays, rollable solar cells, and wearable electronic gadgets [13]. The need for flexible replacements for brittle ITO, however, has been spurred by the flexibility specifications of next-generation optoelectronic devices. Fig. 4 illustrates the schematic circuit of the typical components of conventional supercapacitors and carbon-based flexible ECs. Materials for flexible and transparent electrodes have a lot of potential, including carbon nanotubes (CNTs) [14], metal nanowires [15], metal meshes [16], graphene [17], and conducting polymers [18]. Next-generation solar cells and screens must also be stretchable in addition to transparent and flexible. Stretchability allows for the necessary deformations such as twisting, folding, crumpling, and stretching to be applied conformally to any arbitrary curvilinear surface and to move freely at movable joints. However, simultaneously obtaining high stretchability, superior optical transparency, and low sheet resistance in flexible conductors is a challenging task. Because these characteristic properties face the difficulties in new hybrid-novel structure and designing microstructures or patterned films that can stretch while maintaining the same conductivity, in such as serpentines or mesh-like patterns [13] We provide an overview of the current developments in ITO alternatives in this study, which covers the literature from 2010 to the beginning of 2023. Molecular packing in material design further emphasizes the potential of molecules for the development and design of powerful organic materials and systems. Additionally, this analysis provided a critical evaluation of the challenges and prospects for further investigation [14].

3. Transparent electrodes

A particular class of materials with optical transparency and electrical conductivity are known as transparent electrodes (TEs). Transistors and TEs are vital parts of a lot of contemporary gadgets, including solar panels, liquid crystal displays (LCDs), organic light-emitting diodes (OLEDs), transparent heaters (THs), smart windows, etc. Transparent conductive oxides (TCOs) have historically had a monopoly in the TEs industry. A wide range of practical applications were made possible as early as the 1950s by the development of wide band-gap semiconductors with high optical transparency (>80 %), such as SnO2 and In2O3, and the ability to increase their conductivity by the doping of impurities. Thus, both at the laboratory and industry levels, there is a whole industrial ecosystem and body of knowledge related to TCOs. The most popular TE materials today may be made using advanced vacuum-based sputtering techniques, thanks to more than 60 years of intensive research on indium tin oxide (ITO) films with excellent optical and electrical characteristics. ITO is not appropriate for several applications, especially flexible devices, due to concerns with its ceramic nature and indium shortage. The substantial progress achieved in the quest for novel materials with improved attributes, such more flexibility, stability, a plentiful supply of raw materials, and reduced processing expenses, has threatened the ITO's dominance in the sector. Three primary types of materials are being researched as TE possibilities in addition to TCOs: (i) Conductive polymers such as poly (3,4-ethylenedioxythiophene): poly (styrene sulfonate); (ii) Carbon nanomaterials such as carbon nanotubes (CNTs) or graphene; (iii) Metallic nanostructures such as thin metallic films, metal nanowire or fibre networks, or metal grids [20].

Table 1
Summary of the reported transparent conductive materials with optical transmittance and optical transmittance and low sheet resistance.

Types	Materials	*Trans*-mittance (%)	RS (Ω/sq)	Flexibility	Application	Compatibility With Flexible Substrate
Conductive Polymers	PDMS/PEDOT: PSS [18]	84 %	4.17	Flexible	OSC	Yes
	Acid treated PEDOT: PSS [23]	>90 %	95	Flexible	OLED	Yes
	UV-treated PET/PEDOT: PSS [24]	81 %	57	Flexible	OLED & OSC	Yes
	Ag@f-RGO/PEDOT: PSS [25]	88 %	18	Flexible	–	Yes
Graphene based Electrodes	PET/Single layer Graphene film/Gra HIL [26]	97.70 %	–	Flexible	OLED	Yes
	Graphene Oxide [27]/Graphene PMMA [10]	90 %	40	Flexible	OLED	Yes
	RGO/SWNT/PMMA [26,28]	85 %	153	Flexible	–	Yes
	Graphene RGO-SWCNT hybrid [29]	58.1 % (5th layer)	254	Flexible	OSC	Yes
Metallic Nanowire Electrodes	Embedded Ag network PET [15]	85 %	33	Flexible	OLED	Yes
	Ag NWs PDMS [30]	17.66 %	–	Stretchable	–	No
	Cu NWs PET [13]	84.10 %	23.1	Flexible	–	Yes
	Ag NWs film [31]	80 %	20	Flexible	OLED	Yes
	Au NWs CuNi nano mesh PDMS [32]	77.4–94.1 %	6 to 30	Flexible	–	Yes
	Ag NWs PET [33]	>87 %	<5	Stretchable	OSC	No
	Ag NWs PU [30]	80 %	<10	Flexible	Sensors	Yes
	Ag NWs [34]	88.50 %	0.4	Flexible	Touch Screen	No
	Carbon nanotube [35]	80–90 %	<1000	Flexible	OLED & OSC	Yes
	Metal Nanofibers [36]	~90 %	~1.3	Flexible	OLED	Yes
	CNT/SWNT [37]	78 %	<10	Stretchable	OLED	No
Doped Metal Oxide [9]	Indium Tin Oxide	90 %	100	Stretchable	OLED & OSC	No
	ITO coated PET	72 %	182	Flexible	OSC	Yes
	ITO coated glass	85 %	183	Flexible	OLED	Yes
	PET/ITO	70 %	90	Flexible	OLED	Yes
	PPC/ITO	80 %	145	Flexible	–	Yes
	PPC/ITO/Ag/ITO	68 %	6.5	Flexible	OSC	Yes
Graphene Metallic Nanowire Hybride Electrode	PEDOT: PSS/Ag NWs/ Graphene [38]	83 %	216.6	Flexible	OLED	Yes
	PEDOT: PSS/Ag NWs [38]	84.98 %	183.3	Flexible	Transistor	Yes
	Graphene/Ag NWs Hybrid [17]	94 %	33	Stretchable	Displays	No
	Graphene Metal NW [39]	91 % in visible region	<1	Stretchable	Transistor	No
DMD Electrode	ZnS/Ag/WO3 [40]	>80 %	10 to 20	Flexible	OLED	Yes
	PET/ZnS/Ag/MoO3 [41]	74.22 %	9.74	Flexible	OLED	Yes
Metal mesh	Ag Grid [42]	74	2.8	Flexible	–	Yes
	Graphene/Ag grid [43]	73	12	Flexible & Stretchable	OSC	Yes
	PEDOT:PSS/Ag honeycomb [44]	85	–	Flexible & Stretchable	OLED	Yes
	CNT/Ag grid [14]	88	8.1	Flexible	TCH	Yes
	ITO/Cu grid [16]	82.5	3.8	Flexible	OLED	Yes

ITO's most serious issues might potentially be resolved by these nanomaterials, as demonstrated by the numerous research that have been done on them. Promising candidates among the alternatives are metal-based thermoelectric (TEs) because of their high intrinsic electrical conductivity, their ability to use nanostructures to achieve high optical transparency, and their high propensity to acquire additional properties like stretchability, flexibility, tuneable bandgap alignment, and haziness when combined with other materials. As early as 1877, sputtering and evaporation techniques were used to study and create metallic TEs. It's noteworthy to note that, even though ITO is today the most widely used TE, the earliest recorded uses of TEs were on selenium photoelectric cells in the 1880s, when metallic ultrathin films, such those of silver, gold or platinum, were used. In the beginning, ferroelectric memory, imaging devices, transparent heaters on aircraft windows (for de-icing and de-fogging systems), and solar energy conversion were among of the applications that attracted a lot of attention to metal- and oxide-based TEs. Because metals maintain their high free-electron density (>1022 cm-3) at the nanoscale, metallic nanomaterials are appealing as TEs. The greatest electrical conductor at room temperature is Ag, which has a conductivity of $6.3*10^7$ S/m. As a result, materials based on Ag have a strong chance of functioning as effective TEs. Even though electrodes made of Ag nanostructures have been the subject of several investigations, other metals, such as Cu and Ni–Cu, are now also being investigated. The ductility of metals, as opposed to TCOs, is another benefit. This ductility is further improved when the metal is sculpted at the nanoscale. Contrarily, a disadvantage of having a high free-electron density is that homogeneous metallic

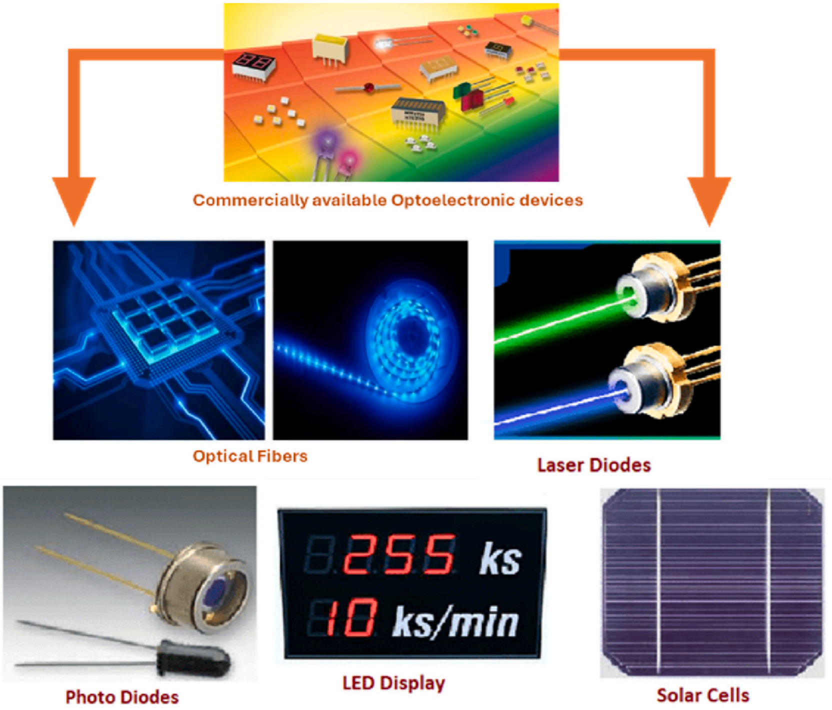

Fig. 3. Commercially available optoelectronic devices.

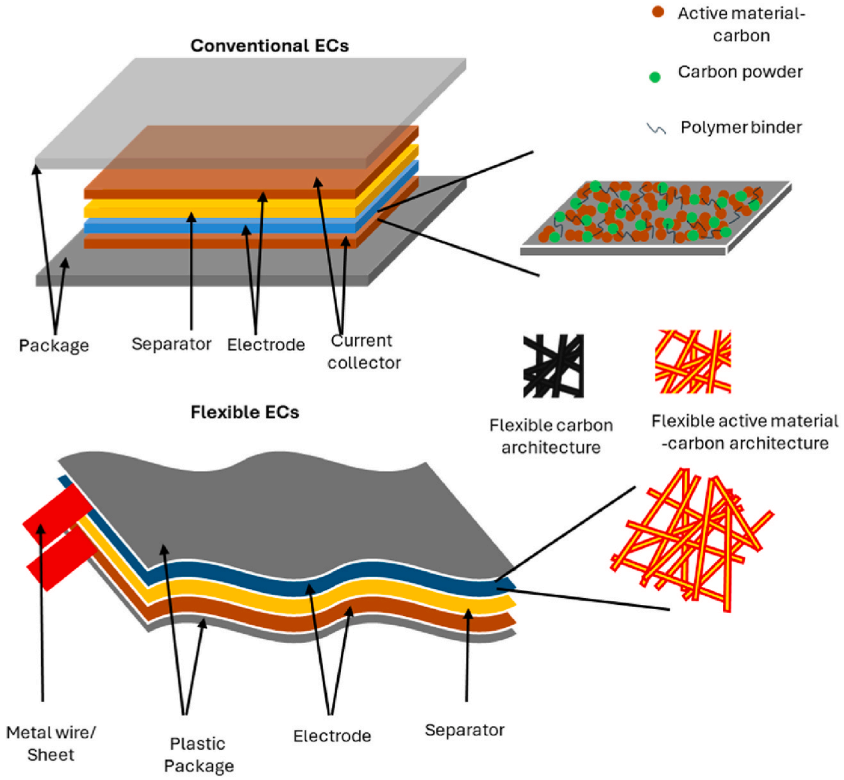

Fig. 4. Schematic illustrations of (a) the typical components of conventional supercapacitors and (b) carbon-based flexible ECs [19].

layers often have low optical transmittance due to metals' high reflectivity. To increase the transparency of metallic-based TEs, several initiatives have been made. Examples of effective TEs include ultrathin metal films and non-continuous metal nanostructures like periodic metal grids and random metal nanowire networks. Although ITO has been employed in a wide range of applications, not all applications call for the same TE standards [20].

Flexible TCEs need to have outstanding optical, electrical, and mechanical characteristics in order to be used in flexible and stretchable or wearable optoelectronics [21], such as OLEDs, OSCs, and touch screens. ITO conductor has become the most widely used TCE material for OLEDs and OSCs in recent years. For commercial ITO thin films, optical transmittance in the visible region is around 80 %, and sheet resistance (Rs) is typically 20 Ω/sq. However, the rare and delicate nature of ITO prevents future advancements in flexible optoelectronic technology. To find alternatives, a variety of materials have been investigated as potential ITO replacements. Six kinds of TCE materials have been suggested for use in OLEDs and OSCs, or organic optoelectronic devices. In this review, we focus on these materials: conductive polymers, graphene-based electrodes, metallic nanowire electrodes, doped metal oxides, hybrid graphene-metallic nanowire electrodes, metal meshes, and dielectric-metallic-dielectric electrodes. The primary traits that are reflective of these six categories are summarized in Table 1 [22].

4. Transparent heaters

The Joule effect serves as the foundation for Transparent heater. J.P. Joule (1818–1889) used experimentation to prove Joule's law, which says that the quantity of heat emitted per unit of time when an electrical current I passes through a homogeneous conductive material with an electrical resistance R is equal to I^2R. Through a balance between heat loss and the Joule effect, the power wasted in the material is directly correlated with the steady state temperature attained. The three main physical origins of these thermal losses—thermal conduction to the substrate or through conducting connections, convection to the surrounding air, and radiation emitted from the hot surfaces—are schematically depicted in Fig. 5. These losses represent the total heat transfer from the thermocouple [45].Increasingly popular as defogging windows and mirrors, transparent heaters and unique resistors that can both produce joule heat and allow visible light through are becoming more and more in demand. Transparent heater performance is primarily determined by two key parameters: optical transmittance and sheet resistance. Transparent heaters with high TR are ideal for periscopes and car windshields, among other applications that need unobstructed vision. In addition to requiring low input power, low sheet resistance is also necessary for sustaining a high saturation temperature quickly [46]. Optical transmittance and sheet resistance must typically make concessions to one another. Due to its exceptional optoelectronic qualities, tin-doped indium oxide (ITO) has had a long-standing dominance in the transparent heating business. The limited flexibility, sluggish temperature response, and rising cost of indium source, however, prevent ITO from finding wider industrial use. Nowadays, metal nanowires (NWs), metal wire meshes, carbon nanotubes (CNTs), graphene, and other hybrid films are being considered as viable alternatives to indium tin oxide (ITO) as transparent conductors or heaters. Because of the high contact resistance between nearby nanotubes and sheets, carbon-based transparent heaters are among those with high RS. Thanks to its high electron concentration, metal NWs and meshes have far superior electrical conductivities. A nonuniform thermal distribution is the consequence of chemically manufactured metal NWs' propensity to cluster together during solution-based dispersion operations [47].

5. Stretchable electrodes and flexible substrates

On stiff substrates that are often brittle and undeform able, traditional electrical and optoelectronic devices are constructed. To interact with people and other settings in novel ways, there is, nevertheless, an increasing requirement for next-generation technologies that can flex and stretch. Stretchable electronics has the potential to create new classes of deformable and stretchable memory, displays, photovoltaics, sensors, electronic skin, energy storage devices, and supercapacitors, revolutionizing the technology of the electronics sector. It is crucial at this point to define the term "stretchable" considering the review's subject and for clarity. Stretchable

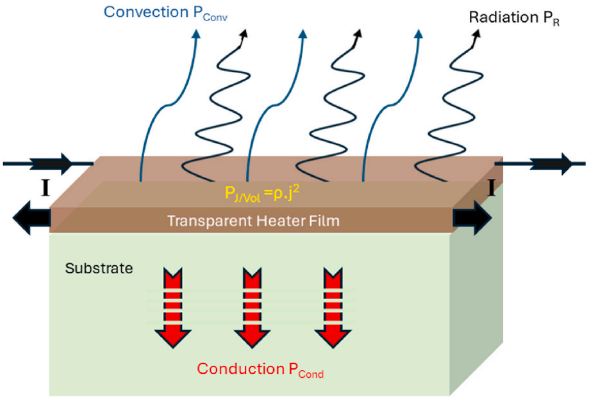

Fig. 5. Schematic diagram of transparent heater.

systems must be more than merely bendable; they must also be flexible. They must also function in the presence of deformations that include significant shape and size changes that might be quite severe [10].

5.1. *Flexible electrochemical supercapacitors (FESCs)*

A flexible electrochemical capacitor (flexible EC) typically consists of separators, liquid and solid electrolytes, symmetric and asymmetric positive/negative electrodes, and a bendable plastic outer container. FESCs, like conventional supercapacitors, are primarily made up of functionalized electrodes, collectors, and an electrolyte. Given that its components must be flexible, FSCs achieve exceptional electrochemical performance by 1) using high-performance, flexible electrodes and 2) employing a flexible electrolyte and collector. Good flexibility is equally crucial for wearable and portable supercapacitors as electrochemical performance. FSCs can exhibit a variety of features and abilities depending on the components used, including compressibility, stretchability, bendability, and twisting. FSCs have distinct properties that make them appropriate for many applications [48]. The major priority of flexible capacitor design is the development of flexible electrode materials for FESC manufacture. Section 7 summarizes contemporary methods for preparing high performance, flexible electrode materials, including as deposition, printing, spraying, and spin techniques.

Among these, the essential electrodes component of a flexible EC are often manufactured from materials containing free-standing carbon. These carbon compounds may act as both electrodes and current collectors and typically have exceptional flexibility and high conductivities. Since the electroactive powder components of the flexible ECs are joined together without the need for binders, conductive additives, or separate current collectors, they are simpler to use than standard ECs. Thus, these adaptable ECs need to exhibit the next two strategic advantages: (1) Device structures: Freestanding carbon materials are used directly as the electrodes and current collectors, whilst soft plastics (such as Teflon films, ethylene/vinyl acetate copolymers, polyethylene terephthalate, and polydimethylsiloxane) are commonly used as the packaging. As a result, these streamlined ECs save a significant amount of weight and space in addition to being thinner, lighter, and more flexible than traditional ECs. (2) Electrode materials: To create an initial paste for classic ECs, certain binders and the crushed electrode material are required. The matching electrodes can then be made by placing the produced paste on a current collector [49]. Therefore, these processes should inevitably lead to the following issues: The long electron-conducting channels in the carbon component are broken down by the asymmetrical mixture of powdered components. Electrolyte cannot penetrate the electrodes because of (i) blocked electroactive material sites; (ii) obstructed electroactive material sites; and (iii) poorly linked void volume, commonly known as “dead volume,” in the electrodes. Electroactive chemicals may be swiftly poured into flexible carbon scaffolds to form the electrodes for flexible ECs. This sort of EC is surprisingly device-ready, able to pick a carbon substrate to regulate the pore’s geometry, and capable of sustaining continuous electron-conducting pathways across the macroscopic carbon scaffold. They can therefore achieve incredible electrochemical performance [19].

5.2. *Conductive polymeric films*

Flexible screens and solar cells have gained attention due to their mobility, low weight, and thinness. Thin films made of polyethylene terephthalate (PET) are used in optoelectronic applications, with transparent electrodes being essential for their effectiveness. However, ITO is brittle and can cause cracks after bending cycles, reducing device dependability. PANI (Polyaniline) [50,51], PEDOT: PSS (poly (3,4-ethylenedioxythiophene) polystyrene sulfonate), a conductive polymer with superior mechanical properties, is considered for electrode films in flexible optoelectronic devices. Treatments like solvents, annealing, or doping with metal nanoparticles can increase PEDOT: PSS’s conductivity. UV ozone treatment is often used to boost PEDOT: PSS work function, but treated films show a two-orders-of-magnitude greater resistance than untreated ones. Low free surface energy of flexible substrates results in poor adherence, necessitating further surface modification. UV pre-treatment of PET is advised to eliminate these problems. There are no reports in the literature on the deposition of PEDOT: PSS films on UV-treated PET to improve conductivity, adhesion, and durability when bent, potentially replacing indium-tin oxide as an electrode coating for displays and solar cells [24].

The chemical structure of PEDOT: PSS [Poly (3,4-ethylenedioxythiophene): poly (styrene sulfonate) [52].

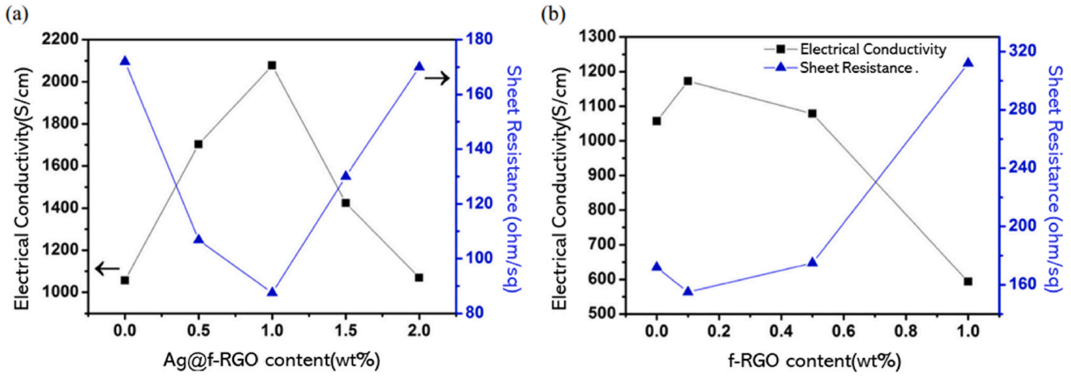

Fig. 6. Electrical conductivity and sheet resistance of the nanocomposite films by varying the content of a) Ag@f-RGO, b) f-RGO in Table 2.

Two different solutions of nanocomposite were prepared and spin-coated on the glass substrate, as shown in Table 1 and Fig. 6, to examine and compare the effects of Ag@f-RGO and f-RGO (functionalization of reduced graphene oxide) integrated in PEDOT: PSS on the electrical characteristics of the nanocomposite films. The resistance of Ag@f-RGO, f-RGO, and PSS thin films as well as pure PEDOT was first measured with a four-point probe. The findings are shown in Table 2. Finally, the electrical conductivity and sheet resistance of the nanocomposite films Ag@f-RGO/PEDOT: PSS and fRGO/PEDOT: PSS, as a function of the graphene concentration, are displayed in Fig. 6a and b, respectfully [25].

Polypyrrole, Polythiophene and Polyaniline are the other conducting polymers which shows high conductivity, adhesion, and durability compared with other conducting polymers. They are commonly used as an Electrically Conductive Adhesive (ECAs). Table 2 denotes the conductivity of the above polymers with RGO. Both PPy and PANI are used as a dopant in the optoelectronic devices the conductivity 40–100 S $cm^{-1}$and 1–100 S cm-1 respectively [53].

The Chemical Structures of Polypyrrole (PPy), Polyaniline (PANI) and Polythiphene (PTh) [54].

5.3. Graphene based electrodes

Due to their high optical transparency and potential for ballistic transport—that is, the ability for electrons to remain unscathed even at room temperature—two-dimensional (2D) materials have been widely recommended as transparent electrodes. Graphene is by far the most advanced 2D material, even though it lacks a bandgap, and it was initially proposed as a potential transparent conductor. In Ref. [3] According to Table 1, the graphene-based electrode materials had an average optical transmittance of around 95 % and an average resistance of about 100 Ω/sq.

The organic optoelectronics community has paid a lot of attention to graphene and its derivatives, including graphene oxide (GO) and reduced graphene oxide (RGO). Their use in BHJ (Bulk Heterojunction) solar cells and PR (Photo Refractive) materials as a replacement for anodes (such as ITO), cathodes, hole transport interlayers (such as PEDOT: PSS replacements), electron extraction interlayers, and electron acceptor has been shown to exist, and problems have been discovered. For instance, graphene sheets' ability to function as electrodes must be enhanced by lowering sheet resistance and enhancing transparency. For graphene to be used as a cathode material, a stronger control over its work function, such as via doping, is required. To employ it as an electron acceptor in blends, the miscibility must be increased [3]. Carrier mobilities higher than 10 000 $cm^2\ V^{-1}\ s^{-1}$ are possible in a graphene monolayer. Thus far, this type of carrier mobility has only been attained in freestanding, nanoscale graphene flakes that are generated by mechanical exfoliation and on films that are created using chemical vapor deposition (CVD) on substrates consisting of boron nitride [56].

5.4. Metallic nanowires electrode (MNWs electrode)

Due to their distinctive qualities, including as high electrical conductivity, flexibility, and transparency, metallic nanowires are frequently utilized as electrodes in a variety of electronic and optoelectronic devices. Silver (Ag), gold (Au), and copper (Cu) are popular candidates for the materials used to create these nanowires, although other materials can also be used. These MNW electrodes are crucial for flexible energy storage devices, antistatic applications, and FTCE (Flexible and Transparent Conductive Electrode) due to its low sheet resistance, solution processability, cheap cost, and ease of scaling. To increase optical transmittance and decrease low resistance, a hybrid made of graphene, or a conducting polymers and metallic nanowire electrodes is utilized. Since metallic nanowires (NW) have exceptional electrical conductivity, optical transparency, and bending resilience against mechanical stress, they are another type of potential TCE material that can replace ITO for flexible electronics. Through solution methods like spin-coating or Mayer rod coating [57], spray coating [58], ink-jet printing [59], or drop casting, metallic NWs may be evenly distributed into solutions and subsequently coated to generate large-scale TCEs. The production method is affordable, sustainable, and reproducible. Metallic nanowires may readily oxidize, and the connections between them can cause significant roughness and unequal R_s [22].

High conductivity, transparency, mechanical flexibility, and simple solution-based processability of AgNWs were demonstrated in several applications. However, the rough surface of optoelectronic devices has several drawbacks, such as poor adhesion, air oxidation, and short circuiting. Graphene has several amazing qualities, including strong in-plane conductivity, great transparency, and mechanical flexibility. In contrast, an excessively high resistance between a transparent conductive electrode's grain boundaries may prevent charge conduction and lower the electrode's total conductivity [33].

The popular conductive polymer is PEDOT: PSS, which is also easily obtained from businesses. Films made with PEDOT: PSS have lesser conductivity than other conductive materials, but they also have certain distinctive properties, including excellent transparency, great mechanical flexibility, better thermal stability, and simple solution-based processing [38].Moreover conductivity of pure PEDOT: PSS could be improved by solvent treatment such as DMSO [60], H_2SO_4 [61], ethylene glycol [62].

Table 4 shows the reported NWs with optical transmittance and low sheet resistivity. It has been investigated recently whether metal nanowires instead of nano troughs may be hybridized with graphene. As far as we know, no assessment has been conducted on

Table 2
Resistance of conducting polymer and graphene materials.

Polymer and graphene thin film	Resistance (Ω)
f-RGO	20×10^{-6}
Ag@f-RGO	18×10^{-6}
Pristine PEDOT: PSS	1075

the potential of this hybrid construction using graphene and nano troughs to enhance the performance of transparent electrodes or develop wearable electronics. Byeong Wan An et al. incorporated 1D nano trough networks onto 2D graphene without significantly reducing T. In this hybrid architecture, the conducting components of nano trough networks and graphene enable simultaneous charge transfer, compensating for the drawbacks of the other component. This electrode can reduce Rs to 1 Ω/sq for a T of 91 % while maintaining electric and optical characteristics consistently under long-term thermal loadings, as shown in Table 1. Making transparent oxide semiconductor transistor arrays that are flexible and act as source/drain and interconnects is one use for this type of hybrid electrode. These arrays of devices have the potential to be used in flexible and wearable electronic systems in the future since they may be affixed to a variety of nonplanar substrates, such as the surfaces of leaves, human skin, and eyeglasses [39].

5.5. *Metal thin films*

Flexible transparent conductive thin films (FTCTFs) are essential components of flexible electronic devices, including touch screens, organic solar cells, flexible transparent heaters, and organic electroluminescent diodes (LEDs). Because of the limitations of the currently available indium tin oxide (ITO) films namely, indium deficiency and ceramic brittleness researchers are compelled to look for alternate materials for FTCTFs. The most promising FTCF materials have been identified as metal nanowires (NWs), particularly Ag and Cu NWs, because to their excellent mechanical, optical, and electrical capabilities [63]. Transparent conductive thin films, or TCFs, are essential parts of many optical-electronic systems, including liquid crystal displays, solar cells, touch panels, solar cells, electromagnetic shielding glass, and organic light-emitting diodes [64]. Metal NWs (Ag NWs and Cu NWs) are now seeing a surge in popularity among loading materials because of their exceptional mechanical and electrical qualities. Additionally, metal NW networks are easily coated using a straightforward and affordable solution coating technique, and they may be distributed like ink. Despite being 100 times less expensive than silver, copper has less stability than silver, thus Cu NW networks perform substantially poorer optoelectrical than Ag NWs. Consequently, Ag NWs have become one of the most promising components of the transparent electrodes of the future [65]. Table 4 shows the materials and their optical transmittance and low sheet resistivity of Ag and Cu NWs and metal thin films.

5.6. *DMD electrode*

An example of an electrode type that combines a metal film, a high-index dielectric layer, and a multilayer high-index dielectric layer is known. It features excellent transmittance along with low sheet resistance and remarkable flexibility. Specifically, the multilayer's high refractive index dielectric layers boost transmittance by reducing the metal film's reflection caused by destructive interference. Work on heat reflecting optical filters was the starting point for earlier experiments on multilayer electrodes. ZnS/Ag/ZnS, WO_3/Ag/MoO_3, ZnS/Ag/MoO_3, Cs_2CO_3/Ag/ZnS applied to OLEDs are a few examples of multilayer electrodes that have been reported by several research groups so far in varied topologies [79]. The Ag films used in these investigations, however, were thicker than 10 nm. Because an increase in Ag film thickness is required to make up for a drop in device transmittance, it may be difficult to fabricate exceptionally transparent OLEDs due to its thickness. The creation of very transparent devices therefore requires the ideal minimum thickness for continuous, low sheet resistance Ag films. As a result of the devices' inability to be transparent and flexible at the same time, multilayer electrodes were used in earlier experiments as either cathodes or anodes.

Reduced transmittance and angular dependence are brought on by the microcavity effect when thicker metal sheets are placed on both sides. As a result, to create TFOLEDs that work, it is first required to address the issues raised in earlier research. OLEDs with multilayer electrodes and excellent transparency were suggested by Kim et al. The created TFOLEDs have better transmittance and can overcome the angular dependence brought on by the microcavity effect. Electron-only devices were created to regulate the ZnS and Cs_2CO_3 layer thickness for the multilayer cathode. Changing the quantity and kind of dielectric layers allowed researchers to investigate the minimal film thickness for continuous Ag film. To increase TFOLED transmittance without sacrificing efficiency, this was done. Optical simulations were used to estimate the ideal ZnS layer thicknesses for antireflection on both the anode side and in the capping layer. PET was used to produce the TFOLEDs' optimal structures. The final product had a peak transmittance of around 550 nm of 74.22 %, and the observed and computed transmittances agreed. The suggested TFOLED design had J-V-L characteristics that were comparable to those reported in investigations where there was no efficiency loss. Additionally, under compressive stress, flexible multilayer electrodes on TFOLEDs remained flexible. Due to the excellent transmittance of these devices, there was little shift in the EL intensity spectra and CIE coordination at different emission angles. Calculations of the microcavity effect's effects were also minimal. We thus believe that the suggested TFOLED architecture is a potential one for use in transparent, flexible displays, as it circumvents issues with earlier work [41].

Table 3
Resistance of conducting polymers and reduced graphene oxide with ZnS [55].

Polymer and graphene thin film	Resistance (Ω)
RGO-PPy	0.18
RGO-PANI	0.21
RGO-PTh	0.17
RGO-PEDOT	0.27

Table 4
Summary of the reported nanowires and films with optical transmittance and optical transmittance and low sheet resistance.

S.No	Fabrication Method	Device	Optical Transmittance	Low sheet Resistance (Ω/sq)	Ref
1	Spin Coating	Ag NWs@SnO2	86.7 %	9.6	[65]
2	Spin Coating	Nb2O5/AgNWs/Nb2O5	84.3 %	9.61	[64]
3	Spin Coating	SnO2/AgNWs bilayer	86.7 %	7.9	[66]
4	Spin Coating	MoO_x/AgNW/MoO_x	89.2 %	12.5	[67]
5	Spin Coating	ATO/AgNWs/ATO	85.7 %	7.1	[68]
6	Spin Coating	Ag@NiO NW	84.8 %	12.1	[69]
7	Spin & spray coating	Al2O3@Cu NWs	84.7 %	15.6	[70]
8	Spin Coating	ATO/CuNWs	85 %	9.6	[71]
9	–	SnO2/Ag/SnO2	94.8 %	9.67	[72]
10	Magnetron sputtering	SnO2/Ag multilayer	81.7 %	–	[73]
11	Magnetron sputtering	AZO/Graphene/Cu/AZO	82 %	4.37	[74]
12	Magnetron sputtering	SnO2/Cu/SnO2	72–80 %	–	[75]
13	Magnetron sputtering	AZO/Ti/Cu/AZO	<82 %	4.31	[76]
14	Sputtering	FTO/SnO2/Cu bi-layer	<82 %	11.01	[77]
15	Magnetron sputtering	Cu-embedded zinc tin oxide (ZTO)	81.2 %	9.92	[78]

5.7. Metal mesh

The flexibility to adjust line width and line pitch to optimize for transparency and sheet resistance makes metal mesh electrodes a top contender for transparent conductors. Lower sheet resistance can be achieved at the expense of reduced transparency by increasing line width or decreasing line pitch. The metal mesh is covered with a transparent film to enhance the conductivity nature and show appropriate resistance and optical transmittance. The metal meshes are easily prepared from the electrospinning technique which is described in section 7.15 To emit light efficiently, OLEDs often require clear electrodes. Indium tin oxide (ITO) is a popular transparent electrode material, although it has certain drawbacks, including brittleness and high production costs. Fig. 7 illustrates the comparison of the transparent electrodes. Metal mesh electrodes, such as silver or copper, provide an alternate approach. They have strong electrical conductivity while being transparent, and they can be made cheaply using technologies like electrospinning, screen printing or photolithography. Metal mesh structures may be built into OLED displays to improve light extraction efficiency. Metal mesh substrates can provide OLED devices flexibility, allowing them to bend or twist without losing performance. Wearable electronics, curved displays, and vehicle illumination are all potential uses for flexible OLEDs. Metal mesh substrates are appropriate for flexible OLED applications because they are mechanically resistant and durable while yet preserving electrical conductivity. Metal meshes can also be employed in OLED devices as an encapsulating or barrier layer. These coatings protect the OLED's organic layers from moisture, oxygen, and other environmental pollutants, increasing its lifespan and stability. Metal meshes can act as conductive barriers, preventing moisture from entering the device structure and providing extra mechanical support. Metal mesh structures can be shaped into pixel arrays to regulate the light output of OLED devices. Pixelation and increased display resolution can be achieved by selectively activating different sections of the metal mesh electrode. This approach is particularly effective for large area displays and signs. Overall, metal mesh provides a diverse framework for improving the performance, functionality, and longevity of OLED displays. Metal mesh, by harnessing its unique qualities like as transparency, conductivity, and flexibility, can overcome critical issues in

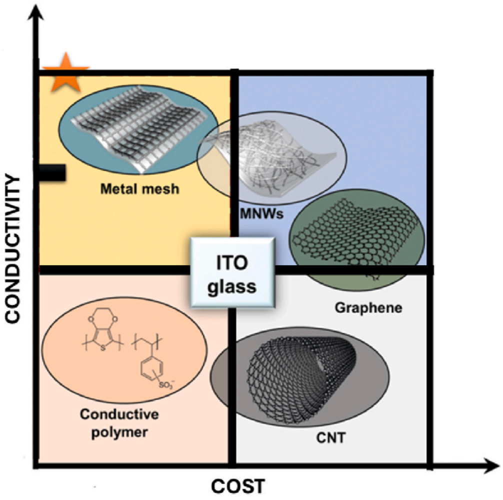

Fig. 7. Diagram illustrating the trade-off between commercial ITO glass and a few possible ITO substitutes, such as graphene, metal nanowires (MNWs), metal mesh, conductive polymers, and carbon nanotubes (CNTs).

OLED production and enable the creation of next generation displays.

6. Functions and recent advancements in the optoelectronic devices

6.1. Functions and recent advances in OLED

The two electroluminescent processes responsible for LED light emission are charge injection and radiative recombination at the p-n junction. Fig. 8a depicts an example of a standard LED device assembly, where the p-type and n-type layers combine to produce the interface's p-n junction. The gadget contains bottom and top electrodes on opposite sides to help with electrical connections, and at least one transparent electrode is added for light extraction. If the bias is forward, the n-type layers will inject electrons into the p-type layers. Light will be released when minority carriers are injected because of their radiative recombination with the dominant carriers across the p-n junction [80].

LED devices have been studied using both organic and inorganic materials. OLEDs are superior to ILEDs in several respects, such as their high mechanical flexibility and inexpensive cost of manufacture, even if their quantum efficiency and long-term stability are still inferior. The exceptional flexibility of the ultrathin OLED has been successfully used to show the LEDs with stretchy emission structures based on organic materials. The majority of flexible or stretchy substrates, on the other hand, are incompatible with ILEDs because they typically need high-temperature manufacturing techniques to deposit the single-crystalline inorganic layers. Alternative strategies include creating efficient ways to move ILEDs from substrates suitable with high temperatures onto stretchy or flexible substrates. Before completely stretchy ILEDs can be produced, the transferred ILEDs still need to be combined with a stretchable and transparent electrode [17].

Electronic gadgets that aid in the visualization of diverse electrical data frequently include displays. Over the last few decades, the development of displays has largely focused on increasing the displays' color range, screen size, and clarity. Research on the earliest flexible organic light-emitting diodes (OLEDs) was reported in 1992 by Gustafsson et al., In 2008, Nokia unveiled the prototype Morph phone, with a flexible screen. Later, flexible displays were added to curved-edge smart phones (Samsung Electronics, 2015) and commercial flexible monitors (Samsung Electronics, 2013) to provide a wider field of vision and more support for user interfaces. Foldable screens often include ultrathin encapsulation layers (transparent polyimide, for example) to survive the extreme mechanical stress applied to the hinge component (bending radius: 41.4 mm) during such recurrent folding tests. LG Electronics unveiled 65-inch rollable screens in 2020 with a total thickness of 5.8 mm and a bending radius of 50 mm. Only the one-way, pre-programmed mobility of certain elements may alter the form of the marketed flexible screens previously stated. Stretchable screens could afford the display industry more alternatives in terms of distinctive form factors considering this constraint [81].

Wearable quantum dot (QD) LEDs (QLEDs) with an ultrathin form factor were disclosed by Choi et al. [82] The geometry of the gadget framework, however, dictated how these screens would always be curved. A foldable display smartphone from Samsung Electronics that can survive more than 200 000 folds in a test of folding cycles was marketed in 2009. As a result, screens' resolution and color purity have virtually reached the upper limits of what the human eye can discern and an increase in demand for different types of cutting-edge displays in recent years, such as those that enable users to flexibly alter the form of the display in accordance with their intended uses (such as boosting mobility, multitasking, and space usage). Flexible screens have been added to smartphones, monitors, and TVs in line with this trend, and recently foldable devices have also been created [10].

Applications for optoelectronics go well beyond those that have been covered thus far. Organic optoelectonic materials have remarkable uses in optically switchable and light-emitting TFTs, memory devices, biosensors, biomimetics, and other fields. The optoelectronic use of organic semiconductors is most well-known for its use in organic light-emitting diodes (OLEDs). A quick summary of recent developments and advancements is provided here, notwithstanding the significant overlap in physical processes and ensuing problems with OLED and device performance that were previously highlighted. The aim of this review is to make a device with more efficiency with enhanced optical transmittance and low sheet resistance [83].

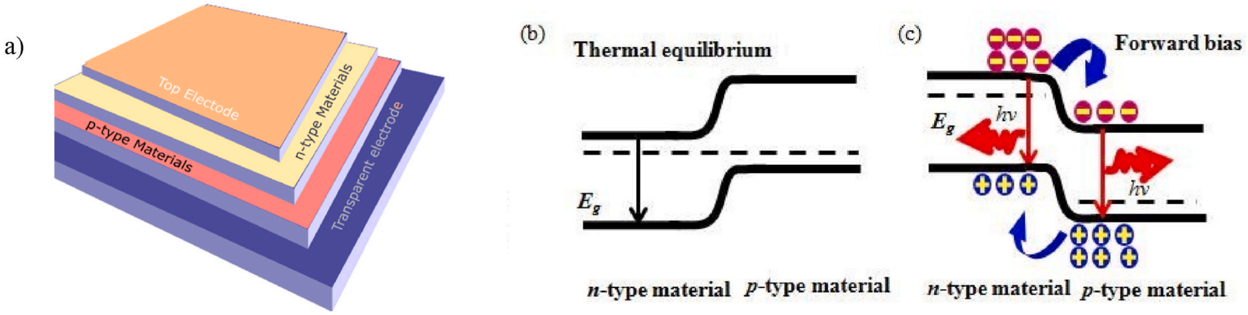

Fig. 8. (a) A schematic showing the device configuration of a LED device. Energy band structures of the *p-n* junction: (b) under thermal equilibrium; (c) under forward bias.

6.2. Functions and recent advances OPV

The market for touch screens and electronic displays has grown significantly during the past ten years. For instance, 362 million touch panels were created in 2010, and from 2010 to 2014, production increased by 20 % annually. Emerging transparent electrode properties including mechanical flexibility, straightforward production techniques, cheap cost, and light weight are also required by emerging device technologies.

OPVs function differently when light is absorbed, as in the case of a bulk heterojunction (BHJ), which combines an acceptor and a donor semiconductor. The electron and hole unite to produce the electron-hole pair known as an exciton because of their opposing charges. Exciton dissociation is the process by which the electron-hole pair split into a cathode and anode. To enhance charge transfer, a layer is positioned in between the active layer and the indium tin oxide (ITO) anode layer in both OLEDs and OPVs. In the case of OPVs, the layer is referred to as the hole extraction layer (HEL), and in the case of OLEDs, as the hole injection layer (HIL). The HIL or HEL layer that is most frequently employed for both devices, poly (3,4-ethylenedioxythiophene): poly (styrene sulfonate, or PEDOT: PSS). Electrostatically conducting conjugated PEDOT (positively charged) and negatively charged PSS (insulating) are gradually diffused in water to form polyelectrolyte PEDOT: PSS. Nevertheless, pure PEDOT: PSS clings to hydrophobic surfaces seldom, has a low conductivity, and is air sensitive. One way to employ nanoparticles (NPs) in stretchy or even flexible devices is to add them to the PEDOT: PSS layer, such as carbon nanotube, gold (Au) NPs, or silver (Ag) NPs. Device efficiency is increased by doping PEDOT: PSS with NPs for a variety of reasons, such as enhanced hole injection, increased conductivity, enhanced plasmonic effect, enhanced scattering, and more. Instead of PEDOT:PSS other conducting polymers also show the reasonable efficiency which is shown in Table 3 [26].

The underlying features of organic materials and device physics, along with advancements in fabrication techniques and device architecture, have led to remarkable progress in the performance of organic optoelectronic devices. There has been a consistent rise in the efficiency of OPVs, and methods to enhance PCEs(Power Conversion Efficiency) through charge transfer state engineering, disorder reduction, and morphological control have been found. Significant improvement is possible because the current performance is still below the estimated thermodynamic limit of more than 20 %. The field of organic photodetector/photo-TFT (Thin film Transistor) technology has made great strides in growth and application. Enhancement of performance and optimization of EQE (External Quantum Efficiency), bandwidth, and detectivity should be facilitated by the introduction of novel high-mobility materials such D-A (donor-acceptor) copolymers, which also display distinct photophysical characteristics and encourage charge separation. Innovations in non-fullerene sensitizers and new photoconductive polymers may significantly enhance the photorefractive dynamics in photorefractive devices, advancing the technique toward commercialization. Organic photorefractive display and imaging has advanced significantly in recent years. Additionally, a variety of innovative photonic uses for photorefractive materials have been theoretically anticipated and/or demonstrated; these applications are still awaiting additional advancements [83].

6.3. Functions and recent advances in OPT

Photodetectors, which are essential devices in numerous industrial and military fields such as thermal efficiency analysis, biomedical sensors, missile guidance, optical communication, video imaging, and night vision, can capture incident light and transform it into detectable electrical signals. Three kinds of photodetectors may be distinguished: photoconductors, photodiodes, and phototransistors. Each category has a unique device architecture and mode of operation. William Shockley invented the phototransistor, a kind of light-sensitive transistor, in 1951 [84], and it has since become one of the key components of optoelectronic integrated circuits. Phototransistors frequently have greater sensitivity and lower noise when compared to photoconductors and photodiodes. In a single device, phototransistors combine the signal-amplification function of a transistor with the light-detecting capabilities of a photodiode. Due to the explosive expansion of organic electronics and the potential application of OPTs in the next generation of portable, human-friendly electronics, research on OPTs has attracted a great deal of attention. When an incident light signal modifies the density of charge carriers in an OFET's (Organic Field-Effect Transistors) active channel, it is known as an OPT (Organic Photodetector). Comparatively speaking, OPTs outperformed regular photodiodes in their ability to detect optical signals. Also, they are easy to integrate into electrical circuits due to their design, which is like that of a complementary metal-oxide-semiconductor (CMOS).

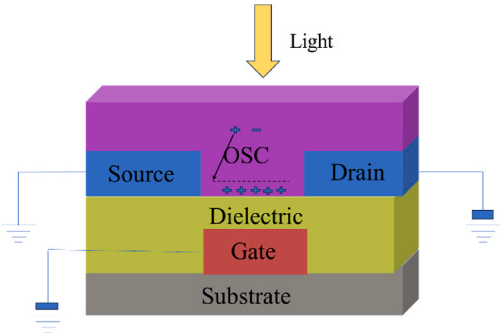

Fig. 9. A typical p-type OPT device structure (TL). During illumination, positive charges drift towards the channel.

Physical processes in OPTs include the following: absorption of light at a certain wavelength; production, diffusion, and dissociation of excitons; and transport of the resulting free charge carriers. Every stage has a major effect on the device's efficacy [85].

The three-terminal stack structure of an OFET is shared by organic phototransistors, a subgroup of organic light detectors. OFETs come in light-emitting (LE) and light-receiving (LR) varieties. Light-receiving OFETs (LR-OFETs) are essentially what OPTs are. Fig. 9 shows a typical OPT device construction. Device configurations include bottom-light (BL) and top-light (TL), respectively, depending on the direction of the light. Typically, the active layer in OFETs and OPTs is made of organic semiconductors (OSCs). They absorb light throughout a broad spectrum of wavelengths, from ultraviolet to near infrared. To create excitons or to cause changes in molecular conformation, the absorbed light stimulates the energy states of molecules. Because of their transistor architecture, OPTs successfully transform light impulses into electrical signals, which they then amplify. Accordingly, they offer both great sensitivity and a low noise level. Organic phototransistors are great choices for low power applications because they can detect weak signals and allow for fine-tuning of the dielectric characteristics. OPTs have been employed for decades in many different disciplines, including biological applications, energy, and environmental investigations [85].

Phototransistors are used in many different fields, including energy, optical memory, industrial process inspection, food and water quality management, biomedical health monitoring, remote diagnostics, electronic eyes, and visible light detection. The sensing of light in the UV and NIR has received special attention in recent OPT advancements. UV sensors are becoming more and more popular in the medical and health sectors to stop sunburn and skin cancer caused by sunshine [83].

The performance of OPTs has improved significantly in recent years, especially in terms of photosensitivity and photodetectivity for low-power applications. Through the synthesis and exploration of novel organic materials, such as blends, small molecules, and polymers, scientists can expand on existing possibilities and achieve optimal device functions. Biocompatibility is an essential criteria for wearable technology. As a result, many options for natural and eco-friendly materials are extensively researched and evaluated. To maintain device high-quality requirements, more work is needed to enhance OPTs' performance in terms of their sensitivity and selectivity to different wavelengths of choice, low power consumption, bending capability sensor lifetime, and environmental stability. With its amazing capabilities, OPT technology has the potential to provide new and exciting opportunities in the rapidly expanding field of information technologies. Synaptic phototransistors won't be shocking to encounter in the near future as artificial intelligence becomes more and more integrated into daily life. Soon, environmentally friendly materials and production methods with high repeatability and unmatched performance efficiency might be used to mass-produce phototransistor-based medical diagnosis and health monitoring sensors, home-assisted devices, and point-of-care (POC) devices at a cheap cost [83,86].

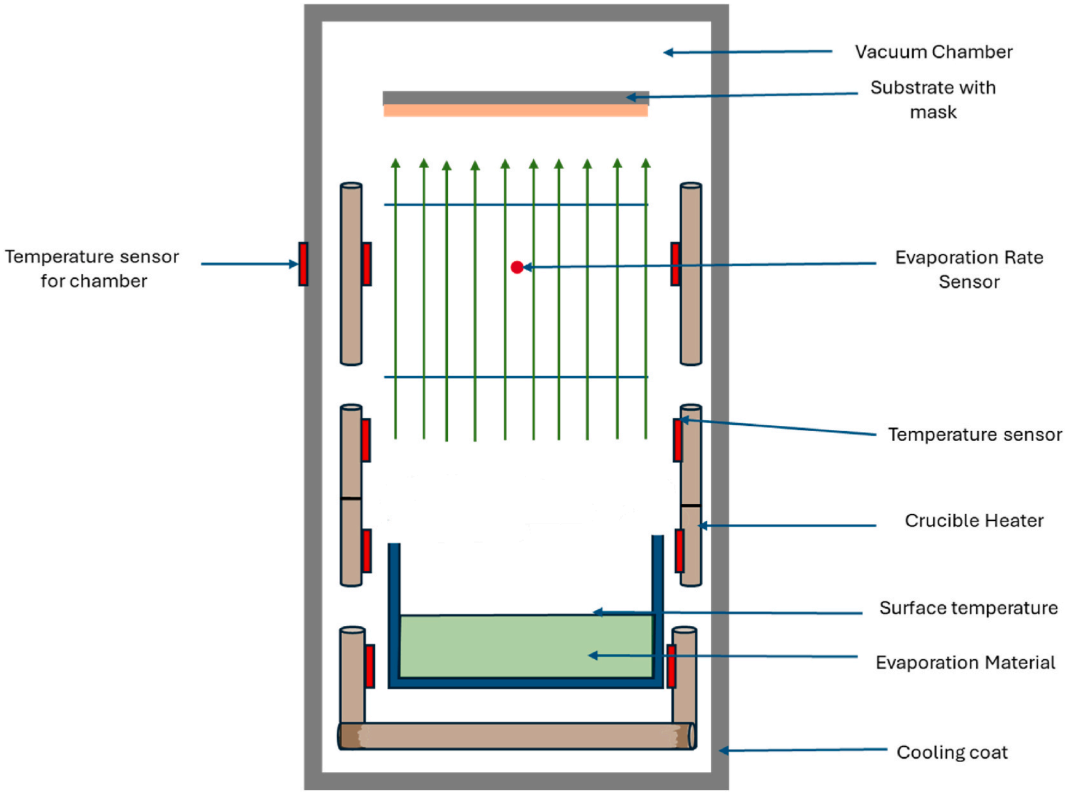

Fig. 10. Scheme of the Vacuum Thermal Evaporation process with multiple heaters [88].

7. Fabrication technique and process of OLED and other optoelectronic devices

There are several methods used to fabricate OLED (Organic Light Emitting Diode) displays. The specific method employed may vary depending on the manufacturer and the type of OLED technology used. Here are some common fabrication methods [87]: Figs. 10–22 shows the schematic images of Fabrication Techniques.

7.1. Vacuum Thermal Evaporation (VTE)

Vacuum thermal evaporation is a widely used method for the fabrication of OLED displays. It involves depositing organic materials onto a substrate by evaporating them in a vacuum chamber. Here is a step-by-step description of the VTE process [51].

1. *Substrate Preparation*: The process starts with preparing the substrate, which is typically a glass or flexible plastic material. The substrate is cleaned and treated to ensure a clean and smooth surface for deposition. 2. *Vacuum Chamber Setup*: The substrate is placed inside a vacuum chamber, which provides a controlled environment for the deposition process. The chamber is sealed and pumped down to a high vacuum to remove any contaminants or gases. 3. *Organic Material Source*: Organic materials, such as small molecules or polymers, are loaded into a crucible or an effusion cell inside the vacuum chamber. The organic material is chosen based on its desired properties, such as emission color, efficiency, and stability. 4. *Heating and Evaporation*: The organic material in the crucible or effusion cell is heated to its evaporation temperature using resistive heating or electron beam heating. As the temperature rises, the organic material starts to sublimate and evaporate. 5. *Deposition onto Substrate*: The evaporated organic molecules travel in a vapor phase and condense onto the substrate. The substrate is usually positioned above the crucible, and the deposition occurs through a process called line-of-sight deposition. 6. *Thin Film Formation*: As the organic molecules condense on the substrate, they form thin films. Multiple layers of different organic materials, such as emissive layers, charge transport layers, and conductive layers, may be sequentially deposited to create the OLED structure. 7. *Monitoring and Control*: During the deposition process, the thickness, uniformity, and composition of the deposited layers are monitored and controlled. Techniques such as quartz crystal microbalance orin-situ monitoring can be used to measure the thickness of the deposited films. 8. *Encapsulation*: Once the OLED layers are deposited, the device may undergo encapsulation to protect it from moisture and oxygen. This step typically involves sealing the OLED structure with a barrier layer and a protective cover, such as glass or flexible encapsulation films.

The VTE process allows for precise control over the thickness and composition of the OLED layers. However, it can be challenging to achieve high deposition rates and large-area uniformity due to the line-of-sight nature of the deposition. Nonetheless, VTE remains a widely used method in OLED fabrication, particularly for small and medium-sized displays [89].

7.2. Inkjet printing

Inkjet printing is a non-contact, digital printing technique that is widely used in various industries, including OLED display fabrication. It involves the precise deposition of small droplets of ink onto a substrate to create patterns or images. Here is a step-by-step description of the inkjet printing process [90,91]: 1. *Ink Preparation*: Inkjet printing requires a specially formulated ink that contains the desired functional materials, such as organic semiconductors, conductive materials, or insulating materials. The ink needs to be carefully developed to ensure proper viscosity, stability, and compatibility with the printing system. 2. *Printing System Setup*: The inkjet printing system consists of an inkjet printhead and a control mechanism. The printhead contains a series of tiny nozzles or microelectromechanical systems (MEMS) that can selectively eject droplets of ink. The control mechanism controls the movement and positioning of the printhead. 3. *Substrate Preparation*: The substrate, usually a glass or flexible plastic material, is prepared by cleaning and treating its surface to ensure proper ink adhesion and uniformity. The substrate is typically mounted on a stage or conveyor system that allows for precise movement during the printing process. 4. *Ink Ejection*: The inkjet printhead moves across the substrate, and the control mechanism triggers the ejection of ink droplets from the nozzles. The droplets are formed by rapidly heating a small volume of

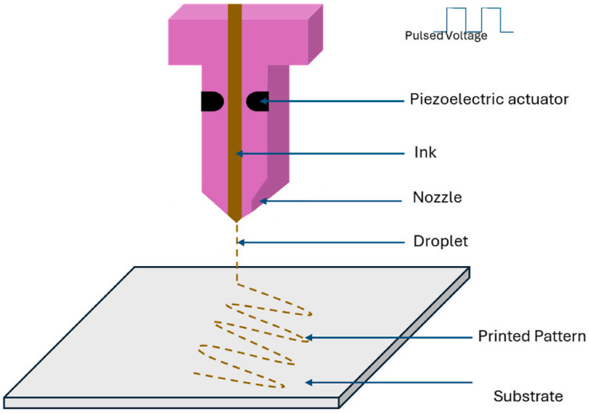

Fig. 11. Schematic of the inkjet printing process.

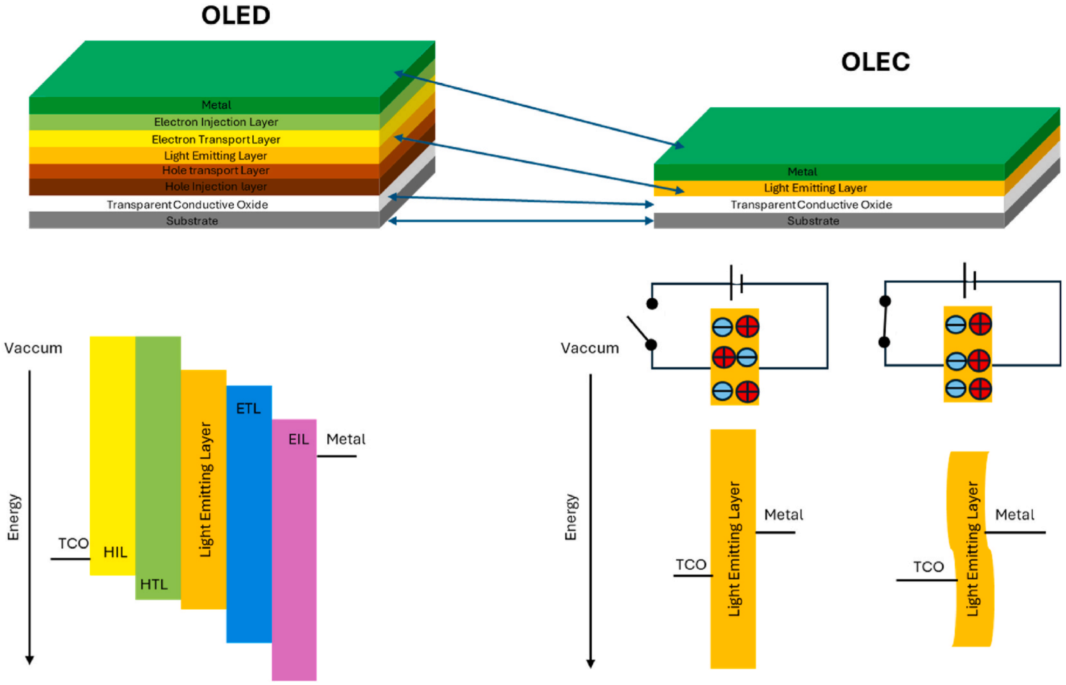

Fig. 12. Comparison of OLED and OLEC layers.

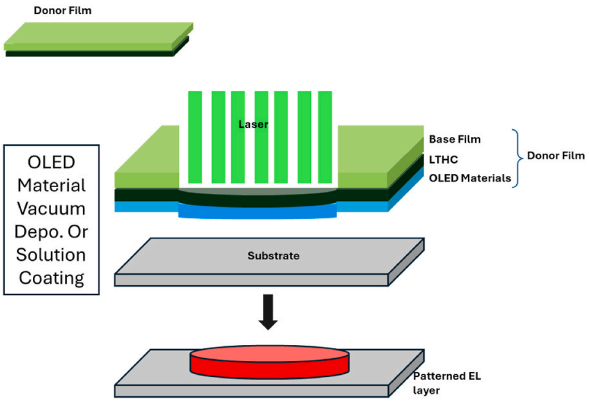

Fig. 13. Schematic of the LITI process [101].

ink, causing it to vaporize and expel from the nozzle. The droplets are then directed towards the substrate. 5. *Droplet Placement*: The droplets of ink are precisely placed on the substrate according to a pre-determined pattern or design. This is achieved by controlling the timing, position, and size of the ejected droplets. The printhead can rapidly switch nozzles on and off to create the desired pattern. 6. *Layer-by-Layer Deposition*: Inkjet printing allows for the sequential deposition of multiple layers to build complex structures. Each layer is printed and dried before the next layer is printed on top. This enables the creation of OLED layers, such as emissive layers, charge transport layers, and conductive layers. 7. *Drying and Curing*: After each layer is printed, it needs to be dried or cured to remove solvents and ensure proper adhesion and stability. This can be achieved through thermal drying, UV curing, or other suitable methods depending on the ink formulation. 8. *Post-Processing*: Once the desired layers are printed and dried, additional post-processing steps may be required. This can include surface treatments, annealing, encapsulation, or other processes to enhance the performance and stability of the printed OLED structure [92,93].

Inkjet printing offers several advantages in OLED fabrication, including high precision, flexibility, scalability, and the ability to print on various substrates. It also allows for rapid prototyping and customization. However, challenges such as ink formulation, nozzle clogging, and limited material compatibility need to be addressed for successful implementation in OLED display production [94–96].

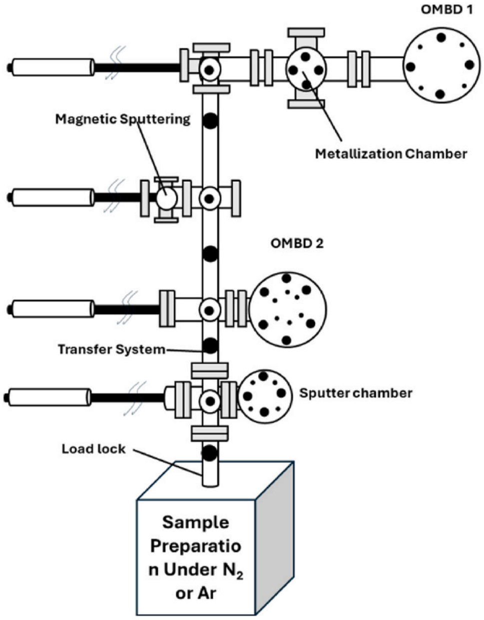

Fig. 14. Thin film Process technique: Organic Molecular Beam Deposition (OMBD) [106].

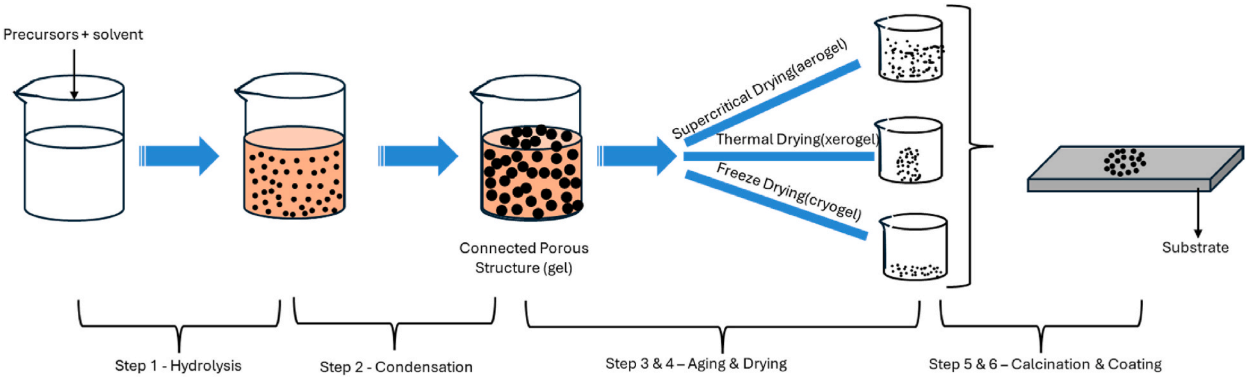

Fig. 15. Schematic diagram of preparation of the Sol-Gel and coated on the substrate [51,92].

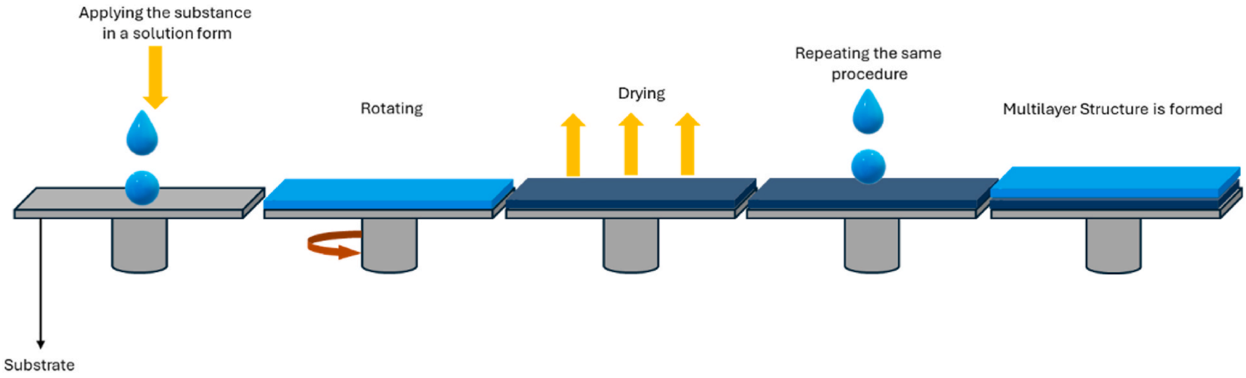

Fig. 16. Process of materials coated on the substate by spin coating technique [108].

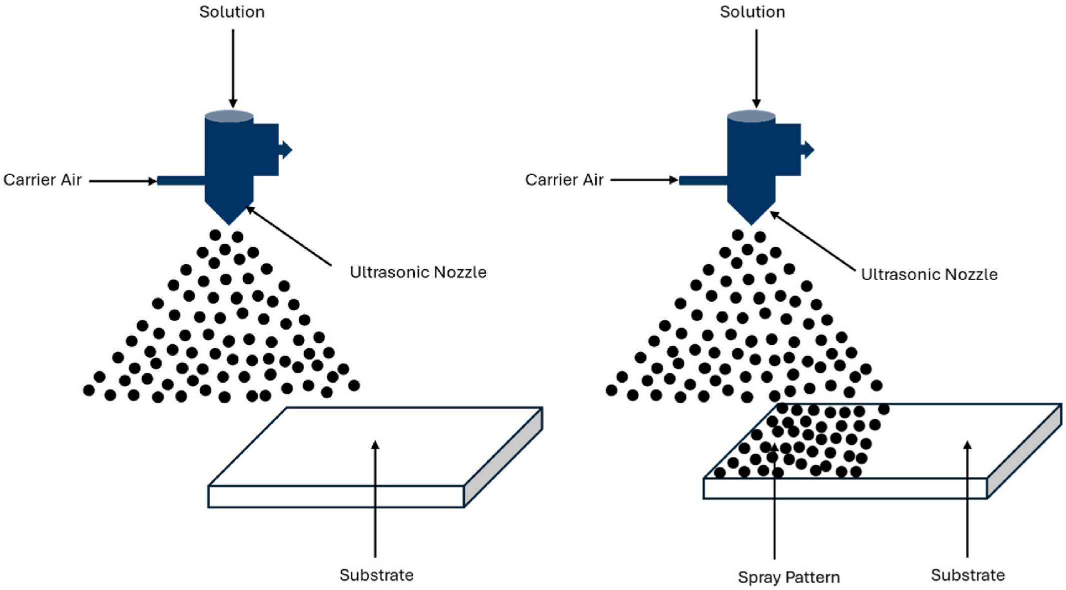

Fig. 17. Schematic of Spray Coating method [88].

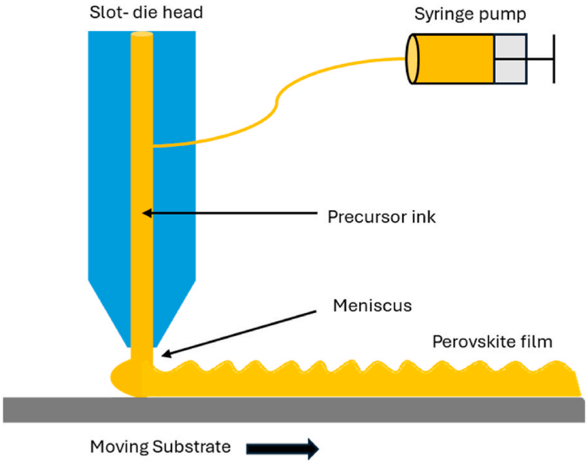

Fig. 18. Slot-die coating process on Substrate [113].

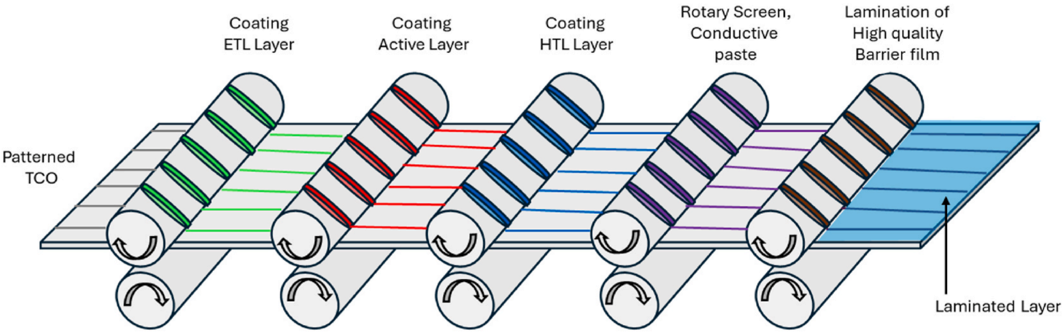

Fig. 19. Schematic image of roll-to-roll printing [92].

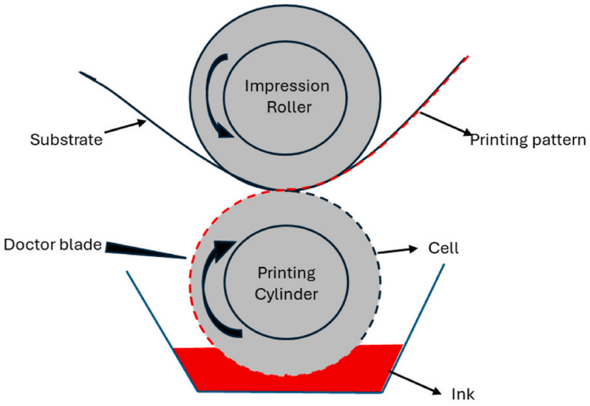

Fig. 20. Schematic image of Gravure Printing [94].

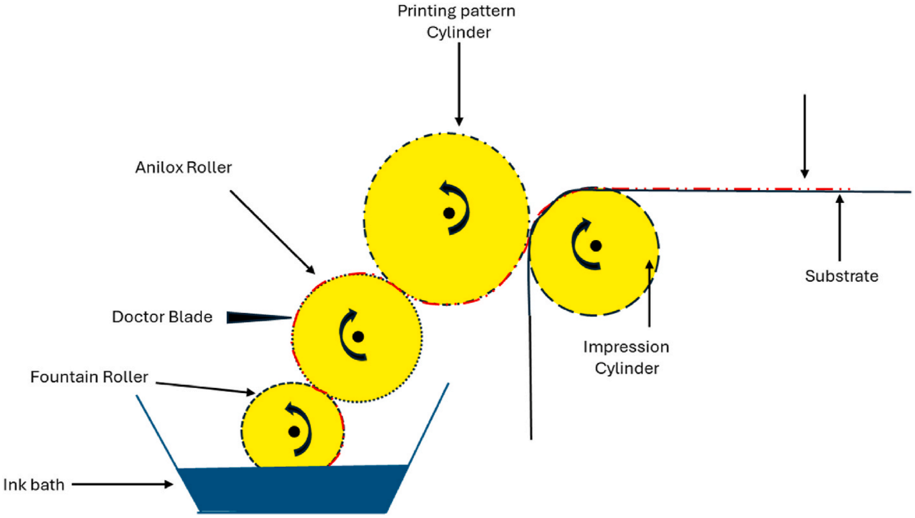

Fig. 21. Schematic image of flexographic printing [118].

7.3. Organic vapor phase deposition (OVPD)

In OLED (Organic Light Emitting Diode) technology, vapor phase deposition is a commonly used technique for the fabrication of organic thin films. Vapor phase deposition allows for the precise control and uniform deposition of organic materials onto a substrate to create the various layers of an OLED device. The vapor phase deposition technique used in OLED fabrication is typically a form of vacuum deposition called organic vapor phase deposition (OVPD). OVPD involves the deposition of organic molecules in the vapor phase onto a substrate under controlled conditions. The process of vapor phase deposition in OLED fabrication involves the following steps [97].

1. *Source Preparation*: The organic materials, also known as the “source materials,” are prepared in solid form. These materials are usually small molecules or polymers that exhibit desired electronic and optical properties. 2. *Vaporization*: The source materials are loaded into a heated crucible or container in a vacuum chamber. The chamber is then evacuated to a low-pressure environment. The source materials are heated to a temperature that allows them to vaporize without decomposing. 3. *Transport and Deposition*: The vaporized organic molecules are transported within the vacuum chamber to the substrate surface, where they condense and form a thin film. The substrate is typically kept at a lower temperature than the source materials to facilitate condensation. 4. *Layer-by-Layer Deposition*: The OLED device structure requires multiple layers, such as the emissive layer, hole transport layer, electron transport layer, and other functional layers. Each layer is deposited sequentially by repeating the vaporization and deposition process with different source materials. 5. *Control of Deposition Parameters*: Various parameters are controlled during the deposition process to achieve the desired film properties. These parameters include temperature, pressure, deposition rate, and substrate positioning. Fine-tuning of these parameters helps achieve uniform film thickness and control the morphology of the deposited layers. 6. *Encapsulation*: After the deposition of the organic layers, the OLED device needs to be encapsulated to protect the organic materials from environmental degradation. Encapsulation is typically done using thin-film barriers or encapsulation layers. Vapor phase deposition in OLED

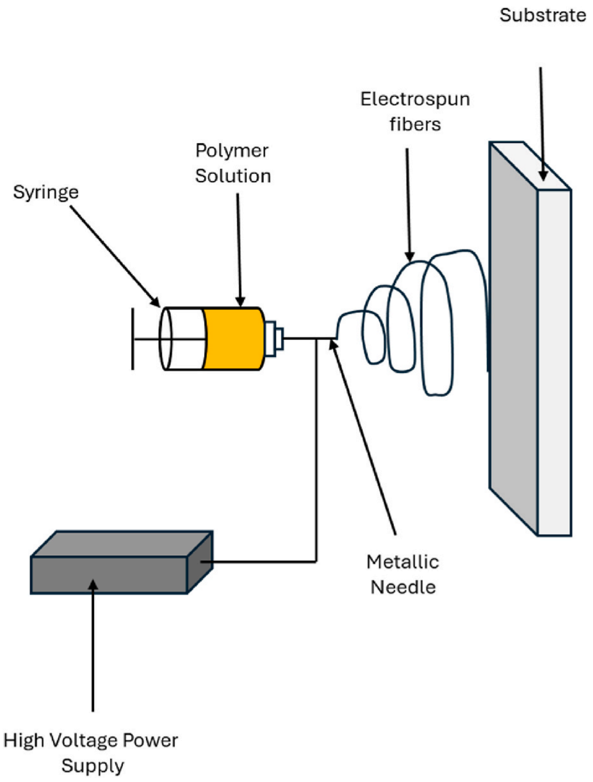

Fig. 22. Schematic Image of Electrospinning technique.

fabrication offers advantages such as high material utilization, good control over layer thickness, and the ability to deposit large-area films. It facilitates the production of high-performance OLED devices with uniform and precise layer structures, leading to improved device efficiency and longevity [98].

7.4. Organic light-emitting electrochemical cells (OLECs)

Organic Light Emitting Electrochemical Cells (OLECs) are a type of OLED technology that combines the principles of electrochemical cells with organic light-emitting materials. OLECs are also known as “ion-polymer OLEDs” or “polymer electrolyte OLEDs.” In OLECs, the device structure typically consists of three main components: the anode, the cathode, and the active layer. The active layer contains an organic semiconductor material that emits light when an electric current passes through it [99].

Here is a general description of the working principle of OLECs:

1. *Anode*: The anode is typically a transparent conductive material, such as indium tin oxide (ITO), which allows light to pass through. It serves as the positive electrode and facilitates the injection of holes (positive charge carriers) into the active layer. 2. *Cathode*: The cathode is usually a low work-function metal or metal alloy, such as aluminum or calcium, which serves as the negative electrode. It facilitates the injection of electrons (negative charge carriers) into the active layer. 3. *Active Layer*: The active layer in OLECs contains an organic semiconductor material that emits light when electrically stimulated. This layer is typically a blend of an electron-donating material (p-type) and an electron-accepting material (n-type). The active layer also includes an electrolyte, which enables ion transport within the device. 4. *Ion Transport*: OLECs utilize an electrolyte that contains mobile ions, such as cations and anions. When a voltage is applied to the device, ions migrate towards the respective electrodes, creating a localized electrochemical environment near the active layer. 5. *Electrochemical Doping*: The migration of ions towards the active layer causes localized electrochemical doping of organic semiconductor materials. This doping leads to the formation of p-doped and n-doped regions within the active layer, which facilitate the injection and transport of holes and electrons, respectively. 6. *Light Emission*: When a voltage is applied, holes and electrons recombine within the active layer, generating excitons. These excitons can decay radiatively, resulting in the emission of light. The emitted light passes through the transparent anode and can be observed [99].

OLECs offer certain advantages over traditional OLEDs. They can be fabricated using solution-based processes, making them compatible with large-area and flexible substrates. Additionally, OLECs can achieve high brightness, low operating voltages, and improved device stability. However, they also have some challenges, such as lower external quantum efficiency compared to traditional OLEDs and the need for careful device design to ensure efficient ion transport and charge balance.

7.5. *Organic material masking*

Organic material masking is a technique used in the fabrication process of Organic Light-Emitting Diode (OLED) displays to selectively deposit or pattern different organic materials. It involves using a mask or a stencil to block or guide the deposition of organic materials onto the substrate. In OLED fabrication, organic materials are typically deposited in thin layers to create different functional components, such as the emissive layer, the charge transport layers, and the electrode layers. These layers need to be precisely patterned to achieve the desired electrical and optical properties of the OLED device.

The organic material masking technique involves the following steps: 1. Mask Design: A mask or stencil is designed, typically made from a material like metal or glass, with predefined patterns or openings that correspond to the desired deposition areas. The mask is designed to allow the organic material to pass through specific regions while blocking it in other areas.2. Mask Alignment: The mask is aligned with the substrate or the previously deposited layers. Alignment ensures that the openings in the mask are positioned accurately over the desired deposition areas. 3. Material Deposition: Organic materials, such as small molecules or polymers, are deposited onto the substrate through the openings in the mask. Deposition techniques can include thermal evaporation, organic vapor phase deposition, or inkjet printing, depending on the specific OLED fabrication process. 4. Mask Removal: Once the organic material deposition is complete, the mask is removed from the substrate. This step is crucial as it allows for the subsequent deposition of other organic materials or layers in different patterns [100].

By using organic material masking, OLED manufacturers can precisely control the deposition of different organic materials, enabling the creation of complex OLED device structures. This technique helps in achieving uniformity, accurate patterning, and efficient utilization of organic materials, resulting in high-performance OLED displays.

7.6. *Laser-induced thermal imaging (LITI)*

Laser-induced thermal imaging (LITI) is a technique used in the fabrication process of Organic Light-Emitting Diode (OLED) displays to pattern and remove unwanted organic materials or layers. It involves the use of a laser to locally heat and evaporate the organic material, which allows for precise and selective removal without damaging the underlying layers [98].

The process of laser-induced thermal imaging in OLED fabrication typically involves the following steps: 1. *Substrate Preparation*: The OLED substrate is prepared by depositing or coating layers of organic materials onto a glass or flexible substrate. These layers can include the emissive layer, charge transport layers, electrode layers, and other functional components. 2. *Mask Design and Alignment*: A photomask or a laser beam pattern is designed to define the desired pattern for material removal. The mask or pattern is aligned with the substrate to ensure accurate positioning. 3. *Laser Exposure*: A laser beam, typically in the infrared range, is directed onto the substrate surface. The laser energy is absorbed by the organic material, causing localized heating and vaporization. This results in the removal of the organic material in the exposed areas. 4. *Selective Material Removal*: The laser-induced thermal energy selectively removes the organic material in the desired pattern, based on the mask or laser beam pattern. The heat generated by the laser evaporates the organic material without damaging the underlying layers or substrate. 5. *Post-Treatment*: After the laser-induced material removal, the substrate may undergo additional processing steps, such as cleaning or deposition of new organic layers, depending on the specific OLED fabrication process.

Laser-induced thermal imaging offers several advantages in OLED fabrication. It allows for precise patterning and removal of organic materials, enabling the creation of complex OLED device structures. It offers high-resolution capabilities, allowing for fine feature sizes. Additionally, LITI is a non-contact and non-mechanical process, minimizing the risk of substrate damage and contamination [102]. Overall, laser-induced thermal imaging is an important technique in OLED manufacturing, facilitating the production of high-performance and high-resolution OLED displays [103].

7.7. *Organic molecular beam deposition (OMBD)*

Organic Molecular Beam Deposition (OMBD) is a technique used in fabrication process of Organic Light-Emitting Diode (OLED) displays to deposit organic thin films with precise control over thickness and composition. OMBD involves evaporation of organic molecules in a vacuum environment and their subsequent deposition onto a substrate to form the different layers of an OLED device [104].

The process of Organic Molecular Beam Deposition in OLED fabrication typically involves the following steps: 1. *Vacuum Chamber Setup*: A vacuum chamber is prepared with substrate holder, organic material sources, and various monitoring and control systems. The chamber is evacuated to create a high-vacuum environment. 2. *Organic Material Evaporation*: Organic materials, such as small molecules or polymers, are loaded into separate crucibles or effusion cells within the vacuum chamber. These organic materials are heated to their evaporation temperature, typically achieved by resistive heating or electron beams. 3. *Molecular Beam Formation*: The heated organic materials vaporize into a molecular beam, which travels in a straight path towards the substrate. The molecular beam is collimated and directed by the design of the chamber, ensuring uniform deposition. 4. *Substrate Deposition*: The substrate, typically a glass or flexible material, is positioned in the path of the molecular beam. The organic molecules condense onto the substrate surface, forming a thin film layer. The deposition process may involve multiple layers, each with different organic materials to achieve specific OLED functionalities. 5. *In-situ Monitoring and Control*: During deposition, various monitoring techniques are employed to measure and control the film thickness, growth rate, and other properties. These techniques can include quartz crystal microbalances, in-situ spectroscopy, or real-time imaging. 6. *Post-treatment*: After deposition, the substrate with the organic layers undergoes additional processing steps, such as thermal annealing or encapsulation, to improve the film morphology, enhance device performance, and protect the OLED structure from environmental factors [105].

In the process of creating OLEDs, organic molecular beam deposition has several benefits. It produces layers that are consistent and clearly defined by enabling exact control over the film's composition and thickness. It gives designers of OLEDs more freedom by permitting the deposition of a broad variety of organic components, including polymers and tiny molecules. Enhancing device performance and efficiency, OMBD also promotes the development of highly ordered and high-quality organic films. For the deposition of organic layers in OLED devices, Organic Molecular Beam Deposition is a dependable and effective process that is essential to OLED manufacture.

7.8. Sol-gel processing

Sol-gel processing is a versatile technique used in the fabrication of Organic Light-Emitting Diode (OLED) displays to deposit organic and inorganic thin films. It involves the conversion of liquid solution into solid gel, which is subsequently processed to form various layers in an OLED device. Sol-gel processing offers advantages such as low-temperature deposition, compatibility with different substrates, and the ability to incorporate different materials [107].

The process of sol-gel processing in OLED fabrication typically involves the following steps:

1. *Sol Preparation*: A sol is prepared by dispersing precursor molecules or nanoparticles in a liquid solvent. The precursor molecules can be organic or inorganic, depending on the desired film composition. The sol may also contain additives such as surfactants or stabilizers to control the particle size and stability of the sol. 2. *Film Deposition*: The sol is deposited onto a substrate using various techniques such as spin coating, dip coating, or inkjet printing. The substrate can be made of glass, plastic, or any other suitable material. The sol is uniformly spread over the substrate, forming a thin liquid film. 3. *Gelation*: After deposition, the sol undergoes gelation, which involves the transformation of the liquid sol into a solid gel network. Gelation can be induced through various mechanisms such as solvent evaporation, chemical reactions, or thermal treatment. During gelation, the sol transforms into a three-dimensional network structure, entrapping the precursor molecules or nanoparticles. 4. *Drying*: Once gelation is complete, the gel is dried to remove the remaining solvent. Drying can be achieved through evaporation or by employing temperature and humidity control. The drying process helps in the removal of the solvent without causing damage to the gel structure. 5. *Calcination (if necessary)*: In some cases, the dried gel may require further treatment such as calcination. Calcination involves heating the gel at high temperatures to promote crystallization, phase transformation, or the removal of residual organics. This step is typically performed for inorganic sol-gel films. 6. *Annealing and Post-treatment*: After the gel is dried or calcined, additional post-treatment steps may be employed to optimize the film properties. Annealing at controlled temperatures can enhance the film's crystallinity, surface morphology, and electrical properties. Other post-treatment techniques, such as surface functionalization or encapsulation, can be applied to improve the film's performance and stability [51,92].

Sol-gel processing offers several advantages in OLED fabrication. It enables the deposition of thin films at relatively low temperatures, making it compatible with flexible substrates. The technique allows for precise control over film thickness and composition, facilitating the fabrication of complex OLED structures. Furthermore, sol-gel processing can be used to incorporate different materials, including organic luminescent molecules, inorganic nanoparticles, or hybrid structures, providing flexibility in OLED design. Overall, sol-gel processing is a versatile and effective technique in OLED fabrication, offering a scalable and cost-effective method for depositing high-quality thin films with tailored properties.

7.9. Spin coating

Spin coating is a commonly used technique in OLED fabrication for depositing thin films onto substrates. Spin coating involves depositing a liquid solution or dispersion onto a substrate and then spinning the substrate at high speeds to spread the solution uniformly. The process typically follows these steps [51]: 1. *Solution Preparation*: A solution or dispersion containing the desired OLED material (e.g., organic molecules or nanoparticles) is prepared. The solution may also contain additives to control the film properties, such as solvents, binders, surfactants, or dopants. 2. *Deposition*: The solution is dispensed onto the substrate, which is usually a flat and rigid material such as glass or silicon. The substrate is placed on a spin coater chuck, and the solution is dropped or pipetted onto the center of the substrate.3. *Spinning*: The substrate is rotated at high speeds, typically ranging from a few hundred to several thousand revolutions per minute (RPM). Centrifugal force causes the solution to spread uniformly over the substrate surface, forming a thin liquid film. 4. *Solvent Evaporation*: During spinning, the solvent in the solution rapidly evaporates due to the high rotational speed and the ambient conditions. The rapid evaporation leads to the formation of a solid thin film composed of the OLED material. 5. *Optional Annealing*: After the spinning process, the deposited film may undergo an annealing step, where it is heated at a controlled temperature for a certain duration. Annealing helps to improve film uniformity, remove residual solvents, and enhance the film's structural and electrical properties.

Spin coating is widely used in OLED fabrication because of its simplicity, low cost, and ability to produce uniform thin films. It enables precise control over film thickness by adjusting factors such as solution concentration, spin speed, and spin time. However, spin coating is more suitable for small-scale production rather than large area displays due to limitations in coating uniformity and scalability [109].

7.10. Spray coating

Spray coating, also known as aerosol jet printing or airbrushing, is another technique used in OLED fabrication. It involves atomizing a liquid solution or dispersion into fine droplets and propelling them towards the substrate. The process can be summarized as follows [51]: 1. *Solution Preparation:* A solution or dispersion containing the OLED material is prepared, like the spin coating process. 2. *Atomization*: The solution is atomized into small droplets using various techniques such as ultrasonic nebulization, pneumatic atomization, or pressure-driven nozzles. The atomized droplets are typically in the micrometer range. 3. *Deposition*: The atomized droplets are propelled towards the substrate using a carrier gas or pressure. The droplets are directed onto the substrate, where they collide and coalesce to form a thin film. 4. *Drying*: After deposition, the solvent in the droplets rapidly evaporates, leaving behind a solid thin film composed of the OLED material. 5. *Optional Annealing*: Like spin coating, an annealing step may be performed to further enhance the film's properties. Spray coating offers advantages such as high deposition rates, scalability, and the ability to coat large-area substrates. It is particularly useful for additive manufacturing processes and for depositing patterned or multi-layered films. However, spray coating may require more precise control over factors such as droplet size, spray angle, and spray distance to achieve uniformity and reproducibility [110].

Both spin coating and spray coating techniques are widely used in OLED fabrication, providing versatile and efficient methods for depositing thin films with tailored properties.

7.11. Slot die coating

Slot Die coating is a commonly used technique in OLED fabrication for depositing thin films onto substrates. It is a continuous and highly controlled coating method that offers advantages in terms of uniformity, precision, and scalability. Here's how the slot die coating process works: 1. *Slot Die Assembly*: The process starts with the assembly of a slot die. [111] A slot die is a specially designed device consisting of a rectangular-shaped slit or channel through which the coating material flows. The dimensions of the slit determine the wet film thickness. 2. *Coating Material Preparation*: A solution or dispersion containing the OLED material is prepared. The solution may also contain additives to control the film properties, such as solvents, binders, surfactants, or dopants. The solution is typically loaded into a reservoir connected to the slot die. 3. *Substrate Preparation*: The substrate, usually a flat and rigid material such as glass or silicon, is cleaned and prepared for coating. It is placed on a moving platform or conveyor belt that passes beneath the slot die. 4. *Coating Process*: As the substrate moves beneath the slot die, the coating material is continuously fed through the slit onto the substrate surface. The gap between the slot die and the substrate determines the wet film thickness. The coating material spreads across the substrate due to capillary forces and fills the entire width of the substrate. 5. *Doctoring Mechanism*: To control the wet film thickness, a doctoring mechanism is often employed. This mechanism consists of a flexible blade or metering roll that skims off excess coating material from the substrate surface, leaving behind a uniform and controlled layer. 6. *Drying*: After coating, the substrate with the wet film is typically passed through a drying or curing process. This process removes the solvent from the coating material, leading to the formation of a solid thin film composed of the OLED material [112].

Slot die coating offers several advantages for OLED fabrication. It allows for precise control of the wet film thickness, resulting in uniform and reproducible layer deposition. The technique is suitable for large-area coating and can achieve high production rates. Additionally, slot die coating can be easily integrated into roll-to-roll manufacturing processes, making it highly scalable for mass production. Overall, slot die coating is a versatile and efficient technique that enables the deposition of thin films in OLED fabrication, contributing to the development of high-performance OLED devices.

7.12. Roll-to-roll printing

Roll-to-roll (R2R) printing is a technique widely used in OLED fabrication for large-scale production of flexible OLED displays. It allows for continuous and high-speed processing of flexible substrates, such as plastic or metal foils, in a roll form. Here's how the roll-to-roll printing process works [114]: 1. *Substrate Preparation*: The process begins with the preparation of a flexible substrate in the form of a roll. This can be a plastic or metal foil with specific properties, such as transparency, flexibility, and heat resistance. The substrate roll is loaded onto a spool or unwinding system. 2. *Printing Methods*: Various printing methods are employed for different layers of OLED devices. These methods includes; a. Solution-Based Printing: Inkjet printing, gravure printing, or screen-printing techniques are used to deposit organic semiconductor materials, such as emitting layers, hole transport layers, and electron transport layers. These printing methods involve the precise deposition of ink formulations containing the OLED materials onto the substrate. b. Vacuum-Based Processes: Techniques such as thermal evaporation or organic vapor phase deposition (OVPD) are utilized to deposit high-purity organic or inorganic materials, such as metal electrodes or barrier coatings. These processes involve the evaporation or sublimation of the materials in a vacuum chamber, followed by their condensation onto the substrate surface. 3. *Multiple Printing Steps*: The R2R process typically involves multiple printing steps to sequentially deposit different layers of the OLED device. Each layer is printed onto the substrate as it moves continuously in a controlled manner. 4. *Drying and Curing*: After each printing step, the printed layers may undergo a drying or curing process to remove solvents, enhance adhesion, or promote chemical reactions. These processes may involve exposure to heat, UV light, or other curing methods. 5. *Inspection and Quality Control*: Throughout the R2R printing process, inspection and quality control measures are implemented to ensure the integrity and uniformity of the printed layers. This may involve inline monitoring systems to detect defects, measure thickness, or assess optical properties. 6. *Roll-to-Roll Lamination and Encapsulation*: Once all the required layers are printed, the flexible OLED structure may undergo lamination and encapsulation processes. These processes involve sealing the OLED layers between protective films or barrier layers to prevent degradation caused by moisture or oxygen. 7. *Roll-to-Roll Cutting and Packaging*: Finally, the continuous OLED structure is cut into individual display panels using roll-to-roll cutting techniques. The panels can then be packaged, tested, and integrated into various display devices [115].

Roll-to-roll printing offers several advantages in OLED fabrication, including high throughput, scalability, and the ability to process large-area flexible substrates. It enables cost-effective production of flexible OLED displays, paving the way for the development of lightweight, bendable, and rollable electronic devices. It is worth noting that specific details of the R2R printing process may vary depending on the printing method, OLED device design, and manufacturing requirements.

7.13. *Gravure printing*

Gravure printing is a widely used technique in OLED fabrication for depositing organic materials onto the substrate. It is a high-resolution printing method that involves engraving tiny cells or wells onto a cylindrical printing plate, which is then filled with ink. The engraved cells hold the ink, and the excess is wiped off the surface. Here is a step-by-step description of the gravure printing technique in OLED fabrication: 1. *Preparation*: The first step involves preparing the printing plate. A cylindrical printing plate, typically made of copper or chrome, is engraved with microscopic cells using a laser or chemical etching. The depth and pattern of the cells determine the amount of ink to be held. 2. *Ink preparation*: The ink used in gravure printing for OLED fabrication consists of organic materials such as light-emitting molecules or conductive materials. The ink must be formulated to meet specific requirements, such as viscosity and stability. 3. *Ink transfer*: The ink is poured onto the engraved printing plate, and a doctor blade or a wiping mechanism removes the excess ink from the surface, leaving only the ink in the engraved cells. 4. *Printing*: The substrate, typically made of glass or plastic, is brought into contact with the inked printing plate. Pressure is applied, either through a roller or a press, to transfer the ink from the cells onto the substrate. The ink adheres to the substrate, forming the desired pattern or layer. 5. *Drying and curing*: After printing, the substrate with the deposited ink is subjected to a drying or curing process, which removes solvents and facilitates the solidification or polymerization of the ink. This step is crucial to ensure the stability and functionality of the printed OLED layers [116, 117].

Gravure printing offers advantages such as high resolution, uniformity, and the ability to print thin and precise layers. It is commonly used in OLED fabrication for various layers, including the emissive layer, hole transport layer, and electron transport layer.

7.14. *Flexographic printing*

Flexographic printing, also known as flex-printing, is a popular printing technique commonly used in the packaging industry. It is a versatile and efficient method that can print on a wide range of substrates, including paper, cardboard, plastic films, and flexible packaging materials. Here is a brief overview of the flexographic printing process:1. *Plate preparation:* Flexographic printing uses flexible printing plates made of rubber or photopolymer materials. These plates are typically mounted on a cylindrical printing plate or sleeve. The plates are customized with raised elements that carry the ink. 2. *Ink preparation*: Ink used in flexographic printing is specially formulated to suit the specific printing requirements. It is typically a water-based or solvent-based ink that is mixed with pigments and additives to achieve the desired color and properties. 3. *Ink transfer*: The ink is transferred from an ink fountain, which contains the ink supply, to the printing plate. An anilox roller with engraved cells rotates through the ink fountain, picking up a controlled amount of ink. The ink is then transferred to the printing plate's raised elements. 4. *Printing*: The substrate, such as paper or film, is fed through the printing press. As the substrate meets the rotating printing plate, the raised elements transfer the ink onto the substrate's surface. The pressure applied and the speed of the printing process can be adjusted to achieve the desired print quality. 5. *Drying and finishing*: After printing, the ink on the substrate needs to be dried or cured. This can be achieved using various methods, such as hot air drying, UV curing, or infrared drying. Additionally, post-printing processes such as laminating, die-cutting, and coating may be performed to further enhance the printed material [90].

Flexographic printing offers several advantages, including high printing speeds, excellent ink transfer efficiency, and the ability to print large volumes. It is commonly used for packaging materials, labels, corrugated cardboard, and flexible packaging applications. These are some techniques for fabricating Optoelectronic devices.

Determining the optimal OLED manufacturing approach among the several techniques listed above is a challenging undertaking. Several parameters, including growing quality requirements, manufacturing volume, and materials utilized in fabrication, influence the choice of OLED fabrication process. The expensive physical vapor deposition method is the most archaic method of manufacture. This method can be substituted by screen printing. The fabrication technique is versatile and economical. However, growing thin films smaller than 100 nm using screen printing is challenging. Ink-jet printing, a non-contact deposition technique, is a manufacturing method for growth on flexible substrates without contamination. The best method for producing OLEDs in large quantities is unquestionably in-line manufacturing. However, roll-to-roll manufacturing will soon overtake other methods as the most compact, particularly for flexible substrates [119].

7.15. *Electrospinning*

Electrospinning is a unique fiber production technology. In the presence of a strong electric field, the polymer solution or melt is spray spun. This approach offers advantages such as simplicity, compatibility with various materials, and continuous fiber preparation [52].To make polymer NF networks, namely, those may be utilized as templates for metal meshes, electrospinning is highly practical. Utilizing electrospun NF networks as templates, Y. Cui's group has recently created a transparent conductor with good performance based on metal nano trough (NTR) mesh [120]. 1. *Selection of Materials*: Choose appropriate organic materials for the various layers of the OLED, including the emissive layer, electron transport layer, and hole transport layer. These materials should have suitable electrical, optical, and morphological properties for efficient OLED operation. 2. *Preparation of Solutions*: Dissolve the selected organic materials in suitable solvents to prepare spinning solutions. The concentration of the materials in the solution should be optimized to achieve the desired nanofiber morphology and uniformity. 3. *Electrospinning Setup:* Set up the electrospinning apparatus, which typically consists of a high-voltage power supply, a syringe pump, a spinneret, and a grounded collector. The spinning solution is loaded into a syringe and pumped through a fine spinneret under the influence of a high electric field. 4. *Formation of Nanofibers*: Apply a high voltage between the spinneret and the collector to create a charged jet of the spinning solution. As the solvent evaporates during flight, nanofibers are formed and deposited onto the grounded collector in a random or controlled manner. 5. *Layer Deposition*: Repeat the electrospinning process to deposit multiple layers of nanofibers corresponding to different OLED components, such as the hole transport layer, emissive layer, and electron transport layer. Each layer may require different spinning parameters to achieve the desired morphology and thickness. 6. *Device Assembly*: After deposition of the electrospun layers, assemble the OLED device by encapsulating the organic layers between suitable electrodes (e.g., anode and cathode). This may involve additional processing steps such as thermal annealing or deposition of additional functional layers. 7. *Characterization and Testing*: Characterize the fabricated OLED device using various techniques such as scanning electron microscopy (SEM), atomic force microscopy (AFM), and optical spectroscopy to evaluate its structural and optoelectronic properties. Test the device performance in terms of brightness, efficiency, and stability under electrical operation. 8. *Optimization and Scale-up*: Optimize the electrospinning process parameters, material formulations, and device architecture to improve OLED performance and reproducibility. Scale up the fabrication process to produce OLEDs on a larger scale for commercial applications.

Electrospinning technique is an impactful fabrication process which is used in the nanofibers, microfibers processing, nanogenarators etc. [121].

8. Future perspective

Organic Light Emitting Diodes (OLED), Organic Solar Cells (OSC) or Organic Photovoltaics (OPV) and Organic Phototransistors (OPT) or Organic Thin Film Transistors (OTFT), their fundamental characteristics, and their potential uses were systematically discussed in this review paper, using notable examples from the literature to bolster our arguments. Since they have an organic semiconductor active layer and an accepted field-effect structure, organic phototransistors have special benefits. Furthermore, the molecular makeup of OSCs may be altered to suit certain purposes. They're better than their inflexible and typical inorganic competitors because of their soft nature and flexible structure. Large-scale manufacturing and prototyping have become more efficient and economical. One of the most critical application fields where flexible electrodes can be effectively used is optoelectronic applications, which includes characteristic of transmittance and resistance; wearable-flexible electronics; optical communication, which includes secure communication of encrypted information through optical memory storage; and environmental monitoring devices.

Stretchable optoelectronic device development has recently made major strides, which has facilitated the creation of electronics that are human-compatible. Various stretchable organic optoelectronic devices, including those for energy harvesting (OPVs), light visualization (OLEDs), and sensing systems (OPTs and OPDs), were reviewed in this review along with their workings. We also detailed the steps needed to develop stretchable electronics with logical choosing materials and structural design by estimating their stretchability under various mechanical stresses. The study looked at both the historical development of organic optoelectronic devices and current research on cutting-edge applications.

Current methods do not fully address the obstacles to producing more complex skin-compatible and human-friendly electronic gadgets. It will be necessary for future intelligent organic optoelectronic devices to integrate multifunctional devices and minimize feature size through precise and fast processing methods to accommodate for complexity. Stretchable optoelectronic devices adhered to human skin may be employed in biomedical diagnostic procedures, in a manner akin to that of smartwatches and smartphones. If long-term vital monitoring is available for patients getting remote diagnosis and supervision, people ought to find it easier to take care of themselves. Artificial sensory electronic devices aim to detect changes in temperature, mechanical, chemical, and physiological signals in the body by imitating human senses. The wellbeing of society can therefore be improved. Therefore, more research into fully integrated systems of optoelectronic components and other electronic components, including as batteries, long-range antenna systems, and electronic circuits, is required0. Stretchable organic optoelectronic device development will go more quickly in the future if we can better understand the underlying material properties and architectural designs of device architecture and create novel approaches to device integration [122].

Up till now, wearable, and flexible optoelectronic technologies have greatly evolved and changed our way of life. Innovative device topologies, light manipulation techniques, transparent conductive electrodes, and novel substrate materials are driving the evolution of high-performance flexible optoelectronic devices. The base is made up of transparent conducting electrodes that are incredibly flexible or stretchable, and the supporting element is substrate materials. The previously mentioned review covers a variety of TCEs composed of metallic nanowires, dielectric-metal hybrid structures, and graphene. The device's efficiency will increase if light extraction or trapping components are included. A new age of flexible and wearable optoelectronic devices will be ushered in by increasing commercial and technical needs. Future technology will undoubtedly allow for the development of electrical devices that can be rolled, folded, twisted, and even incorporated with the human body [123].

9. Conclusion

As we peer into the horizon of upcoming electronics technology, one thing becomes abundantly clear: stretchable electronics are poised to assume a pivotal role in shaping the landscape of innovation. The extensive evolution of flexible transparent organic optoelectronic devices, as highlighted in this review, heralds an era where imaginative applications previously deemed unattainable with standard rigid electronics are now on the cusp of realization. The allure of stretchable electronics lies in their ability to adapt to arbitrary surfaces and incorporate movable components, a feat that remains elusive for conventional rigid electronics. This transformative capability opens the doors to an array of exciting possibilities. Stretchable electronic devices not only promise reversibly foldable and stretchable conformal integrated circuits but also wearable displays capable of transmitting information while allowing users to see through them. Furthermore, these devices extend their potential to encompass energy storage and communication solutions that can seamlessly conform to curved surfaces, such as building arches or the exteriors of automobiles. The realm of biomedical systems stands to benefit immensely from stretchable electronics, with the ability to integrate with the human body in ways that were once the stuff of science fiction. Imagine surgical implants that seamlessly harmonize with the body, revolutionizing the healthcare industry and patient care.

Additionally, the emergence of stretchable electronics will also empower the creation of robotic systems featuring soft and mobile components, paving the way for more versatile and adaptable robotic technology. Our journey through the evaluation of existing literature has been a source of great satisfaction, as it has become evident that the field of stretchable electronics is brimming with promise and potential. The release of numerous high-quality papers across various journals reflects the dedication and ingenuity of researchers in this domain. With these remarkable advancements, it is only a matter of time before stretchable electronics take center stage in the future of technology, illuminating the path towards unprecedented innovations and applications. The potential is vast, and the future is bright for stretchable electronics.

CRediT authorship contribution statement

Kavinkumar Ravikumar: Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Milind Shrinivas Dangate:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that there is no conflict of interest.

References

[1] H. Lee, Z. Jiang, T. Yokota, K. Fukuda, S. Park, T. Someya, Stretchable organic optoelectronic devices: design of materials, structures, and applications, Mater. Sci. Eng. R Rep. 146 (Oct. 2021), https://doi.org/10.1016/j.mser.2021.100631.

[2] A. Pandiyan, et al., A comprehensive review on perovskite and its functional composites in smart textiles: progress, challenges, opportunities, and future directions, Prog. Mater. Sci. 140 (2023), https://doi.org/10.1016/j.pmatsci.2023.101206.

[3] O. Ostroverkhova, Organic optoelectronic materials: mechanisms and applications, Chem. Rev. 116 (22) (Nov. 23, 2016) 13279–13412, https://doi.org/10.1021/acs.chemrev.6b00127. American Chemical Society.

[4] L. Veeramuthu, et al., Human skin-inspired electrospun patterned robust Strain-insensitive pressure sensors and wearable flexible light-emitting diodes, ACS Appl. Mater. Interfaces 14 (26) (Jul. 2022) 30160–30173, https://doi.org/10.1021/acsami.2c04916.

[5] K. Ravikumar, M.S. Dangate, Transparent photovoltaics and environmental impact, Smart Grids as Cyber Physical Systems 2 (2024) 247.

[6] A. Salehi, X. Fu, D.H. Shin, F. So, Recent advances in OLED optical design, Adv. Funct. Mater. 29 (15) (Apr. 11, 2019), https://doi.org/10.1002/adfm.201808803.

[7] Z. Chen, S.N. Obaid, L. Lu, Recent advances in organic optoelectronic devices for biomedical applications, Opt. Mater. Express 9 (9) (Sep. 2019) 3843, https://doi.org/10.1364/ome.9.003843.

[8] Z. Hu, et al., Energy-level alignment at the organic/electrode interface in organic optoelectronic devices, Adv. Funct. Mater. 26 (1) (Jan. 2016) 129–136, https://doi.org/10.1002/adfm.201503420.

[9] W. Cao, J. Li, H. Chen, J. Xue, Transparent electrodes for organic optoelectronic devices: a review, J. Photon. Energy 4 (1) (Oct. 2014) 040990, https://doi.org/10.1117/1.jpe.4.040990.

[10] J. Zhao, et al., Recent developments of truly stretchable thin film electronic and optoelectronic devices, Nanoscale 10 (13) (Apr. 07, 2018) 5764–5792, https://doi.org/10.1039/c7nr09472h.

[11] T. Pan, S. Liu, L. Zhang, W. Xie, iScience Flexible Organic Optoelectronic Devices on Paper, 2021, https://doi.org/10.1016/j.isci.

[12] H.B. Lee, W.Y. Jin, M.M. Ovhal, N. Kumar, J.W. Kang, Flexible transparent conducting electrodes based on metal meshes for organic optoelectronic device applications: a review, J. Mater. Chem. C 7 (5) (2019) 1087–1110, https://doi.org/10.1039/c8tc04423f.

[13] C. Hwang, et al., Controlled aqueous synthesis of ultra-long copper nanowires for stretchable transparent conducting electrode, J Mater Chem C Mater 4 (7) (2016) 1441–1447, https://doi.org/10.1039/C5TC03614C.

[14] Z. Zhong, et al., Defect-free, highly uniform washable transparent electrodes induced by selective light irradiation, Small 14 (21) (May 2018), https://doi.org/10.1002/smll.201800676.

[15] A.R. Madaria, A. Kumar, C. Zhou, Large scale, highly conductive and patterned transparent films of silver nanowires on arbitrary substrates and their application in touch screens, Nanotechnology 22 (24) (Jun. 2011), https://doi.org/10.1088/0957-4484/22/24/245201.

[16] D.H. Cho, et al., Flexible integrated OLED substrates prepared by printing and plating process, Org. Electron. 50 (Nov. 2017) 170–176, https://doi.org/10.1016/j.orgel.2017.07.041.

[17] M.S. Lee, et al., High-performance, transparent, and stretchable electrodes using graphene-metal nanowire hybrid structures, Nano Lett. 13 (6) (Jun. 2013) 2814–2821, https://doi.org/10.1021/nl401070p.

[18] X. Fan, B. Xu, S. Liu, C. Cui, J. Wang, F. Yan, Transfer-printed PEDOT:PSS electrodes using mild acids for high conductivity and improved stability with application to flexible organic solar cells, ACS Appl. Mater. Interfaces 8 (22) (Jun. 2016) 14029–14036, https://doi.org/10.1021/acsami.6b01389.

[19] Y. He, W. Chen, C. Gao, J. Zhou, X. Li, E. Xie, An overview of carbon materials for flexible electrochemical capacitors, Nanoscale 5 (19) (Oct. 07, 2013) 8799–8820, https://doi.org/10.1039/c3nr02157b.

[20] V. H. Nguyen et al., "Advances in flexible metallic transparent electrodes," Advances in Flexible Metallic Transparent Electrodes. Small, vol. 2022, no. 19, p. 2106006, doi: 10.1002/smll.202106006ï.

[21] X. Ding, E. Shen, Y. Zhu, J.M. Moran-Mirabal, Stretchable thin film inductors for wireless sensing in wearable electronic devices, Flexible and Printed Electronics 7 (3) (Sep. 2022), https://doi.org/10.1088/2058-8585/ac8c50.

[22] H. Zhu, Y. Shen, Y. Li, J. Tang, Recent advances in flexible and wearable organic optoelectronic devices, J. Semiconduct. 39 (1) (Jan. 2018), https://doi.org/10.1088/1674-4926/39/1/011011.

[23] A. Fallahzadeh, J. Saghaei, T. Saghaei, Ultra-smooth poly(3,4-ethylene dioxythiophene):poly(styrene sulfonate) films for flexible indium tin oxide-free organic light-emitting diodes, J. Lumin. 169 (Jan. 2016) 251–255, https://doi.org/10.1016/j.jlumin.2015.09.021.

[24] M. Aleksandrova, N. Kurtev, V. Videkov, S. Tzanova, S. Schintke, Material alternative to ITO for transparent conductive electrode in flexible display and photovoltaic devices, Microelectron. Eng. 145 (Apr. 2015) 112–116, https://doi.org/10.1016/j.mee.2015.03.053.

[25] C. Te Hsu, C. Wu, C.N. Chuang, S.H. Chen, W.Y. Chiu, K.H. Hsieh, Synthesis and characterization of nano silver-modified graphene/PEDOT:PSS for highly conductive and transparent nanocomposite films, J. Polym. Res. 22 (10) (Oct. 2015), https://doi.org/10.1007/s10965-015-0847-7.

[26] Z. Liu, P. You, C. Xie, G. Tang, F. Yan, Ultrathin and flexible perovskite solar cells with graphene transparent electrodes, Nano Energy 28 (Oct. 2016) 151–157, https://doi.org/10.1016/j.nanoen.2016.08.038.

[27] A. Ubah, N. Zakeri, M. Cerruti, T. Szkopek, High resistivity free-standing crosslinked graphene oxide substrates: hopping conduction mechanism and application to recyclable electronics, Flexible and Printed Electronics 8 (3) (Sep. 2023), https://doi.org/10.1088/2058-8585/acf8d5.

[28] H.J. Lee, Y.S. Song, T.K. An, W.K. Choi, S.R. Kim, Ultrasmooth transparent conductive hybrid films of reduced graphene oxide and single-walled carbon nanotube by ultrasonic spraying, Synth. Met. 221 (Nov. 2016) 340–344, https://doi.org/10.1016/j.synthmet.2016.10.012.

[29] J.H. Huang, J.H. Fang, C.C. Liu, C.W. Chu, Effective work function modulation of graphene/carbon nanotube composite films as transparent cathodes for organic optoelectronics, ACS Nano 5 (8) (Aug. 2011) 6262–6271, https://doi.org/10.1021/nn201253w.

[30] E.H. Ko, H.J. Kim, S.M. Lee, T.W. Kim, H.K. Kim, Stretchable Ag electrodes with mechanically tunable optical transmittance on wavy-patterned PDMS substrates, Sci. Rep. 7 (2017), https://doi.org/10.1038/srep46739.

[31] H. Kang, et al., Flexible and mechanically robust organic light-emitting diodes based on photopatternable silver nanowire electrodes, J. Phys. Chem. C 120 (38) (Sep. 2016) 22012–22018, https://doi.org/10.1021/acs.jpcc.6b06599.

[32] J.H.M. Maurer, L. González-García, B. Reiser, I. Kanelidis, T. Kraus, Templated self-assembly of ultrathin gold nanowires by nanoimprinting for transparent flexible electronics, Nano Lett. 16 (5) (May 2016) 2921–2925, https://doi.org/10.1021/acs.nanolett.5b04319.

[33] L. Zhou, et al., High-performance flexible organic light-emitting diodes using embedded silver network transparent electrodes, ACS Nano 8 (12) (Dec. 2014) 12796–12805, https://doi.org/10.1021/nn506034g.

[34] D.W. Jeong, N.S. Jang, K.H. Kim, J.M. Kim, A stretchable sensor platform based on simple and scalable lift-off micropatterning of metal nanowire network, RSC Adv. 6 (78) (2016) 74418–74425, https://doi.org/10.1039/c6ra15385b.

[35] L. Hu, H.S. Kim, J.Y. Lee, P. Peumans, Y. Cui, Scalable coating and properties of transparent, flexible, silver nanowire electrodes, ACS Nano 4 (5) (May 2010) 2955–2963, https://doi.org/10.1021/nn1005232.

[36] J. Jang, et al., Rapid production of large-area, transparent and stretchable electrodes using metal nanofibers as wirelessly operated wearable heaters, NPG Asia Mater. 9 (9) (2017), https://doi.org/10.1038/am.2017.172.

[37] S. Ahn, et al., Directed self-assembly of rhombic carbon nanotube nanomesh films for transparent and stretchable electrodes, J Mater Chem C Mater 3 (10) (2015) 2319–2325, https://doi.org/10.1039/C4TC02733G.

[38] Y. Altin, M. Tas, I. Borazan, A. Demir, A. Bedeloglu, Solution-processed transparent conducting electrodes with graphene, silver nanowires and PEDOT: PSS as alternative to ITO, Surf. Coat. Technol. 302 (Sep. 2016) 75–81, https://doi.org/10.1016/j.surfcoat.2016.05.058.

[39] B.W. An, et al., Stretchable and transparent electrodes using hybrid structures of graphene-metal nanotrough networks with high performances and ultimate uniformity, Nano Lett. 14 (11) (Nov. 2014) 6322–6328, https://doi.org/10.1021/nl502755y.

[40] H. Cho, C. Yun, J.W. Park, S. Yoo, Highly flexible organic light-emitting diodes based on ZnS/Ag/WO3 multilayer transparent electrodes, Org. Electron. 10 (6) (2009) 1163–1169, https://doi.org/10.1016/j.orgel.2009.06.004.

[41] D.Y. Kim, Y.C. Han, H.C. Kim, E.G. Jeong, K.C. Choi, Highly transparent and flexible organic light-emitting diodes with structure optimized for anode/cathode multilayer electrodes, Adv. Funct. Mater. 25 (46) (Dec. 2015) 7145–7153, https://doi.org/10.1002/adfm.201502542.

[42] J.A. Jeong, J. Kim, H.K. Kim, Ag grid/ITO hybrid transparent electrodes prepared by inkjet printing, Sol. Energy Mater. Sol. Cell. 95 (7) (Jul. 2011) 1974–1978, https://doi.org/10.1016/j.solmat.2011.02.016.

[43] Y.H. Kahng, et al., Highly conductive flexible transparent electrodes fabricated by combining graphene films and inkjet-printed silver grids, Sol. Energy Mater. Sol. Cell. 124 (May 2014) 86–91, https://doi.org/10.1016/j.solmat.2014.01.040.

[44] L. Kinner, et al., Inkjet-printed embedded Ag-PEDOT:PSS electrodes with improved light out coupling effects for highly efficient ITO-free blue polymer light emitting diodes, Appl. Phys. Lett. 110 (10) (Mar. 2017), https://doi.org/10.1063/1.4978429.

[45] H.B. Lee, W.Y. Jin, M.M. Ovhal, N. Kumar, J.W. Kang, Flexible transparent conducting electrodes based on metal meshes for organic optoelectronic device applications: a review, Royal Society of Chemistry, J. Mater. Chem. C 7 (5) (2019) 1087–1110, https://doi.org/10.1039/c8tc04423f.

[46] M. Gueye, A. Carella, R. Demadrille, J.-P. Simonato, M.N. Gueye, All-polymeric flexible transparent heaters, ACS Appl. Mater. Interfaces 9 (32) (2017) 27250–27256, https://doi.org/10.1021/ac.

[47] P. Li, et al., Flexible transparent heaters based on silver nanotrough meshes, J. Alloys Compd. 664 (Apr. 2016) 764–769, https://doi.org/10.1016/j.jallcom.2015.12.216.

[48] Z. Yan, S. Luo, Q. Li, Z.S. Wu, S. Liu, Recent advances in flexible wearable supercapacitors: properties, fabrication, and applications, Adv. Sci. 11 (8) (2024), https://doi.org/10.1002/advs.202302172.

[49] T.K. Hatwar, et al., Development in OLED formulations with improved efficiency and stability, in: Organic Light-Emitting Materials and Devices VIII, SPIE, Nov. 2004, p. 1, https://doi.org/10.1117/12.567418.

[50] E.I. Yesilyurt, et al., Screen printable PANI/carbide-derived carbon supercapacitor electrode ink with chitosan binder, Flexible and Printed Electronics 8 (4) (Dec. 2023), https://doi.org/10.1088/2058-8585/ad0ebd.

[51] S. A. Sajedi, M. M. Bagheri-Mohagheghi, and A. Shirpay, “PANI/SnO 2 Nanoparticle, FTO/PET and Al/PET as Hybrid Nanocomposite Soft Electrodes Synthesized by Sol-Gel, Spray Pyrolysis and Thermal Vacuum Evaporation Methods”, doi: 10.1007/s12034-023-03081-4S.

[52] C. Buga, J. C Viana, Optimization of print quality of inkjet printed PEDOT:PSS patterns, Flexible and Printed Electronics 7 (4) (Dec. 2022), https://doi.org/10.1088/2058-8585/ac931e.

[53] H. Derakhshankhah, et al., Conducting polymer-based electrically conductive adhesive materials: design, fabrication, properties, and applications, J. Mater. Sci. Mater. Electron. 31 (14) (Jul. 01, 2020) 10947–10961, https://doi.org/10.1007/s10854-020-03712-0.

[54] X. Wu, W. Fu, H. Chen, Conductive polymers for flexible and stretchable organic optoelectronic applications, ACS Appl. Polym. Mater. 4 (7) (Jul. 08, 2022) 4609–4623, https://doi.org/10.1021/acsapm.2c00519. American Chemical Society.

[55] Z. Xu, et al., Investigation on the role of different conductive polymers in supercapacitors based on a zinc sulfide/reduced graphene oxide/conductive polymer ternary composite electrode, RSC Adv. 10 (6) (2020) 3122–3129, https://doi.org/10.1039/c9ra07842h.

[56] M. Morales-Masis, S. De Wolf, R. Woods-Robinson, J.W. Ager, C. Ballif, Transparent electrodes for efficient optoelectronics, Advanced Electronic Materials 3 (5) (2017), https://doi.org/10.1002/aelm.201600529. Blackwell Publishing Ltd, May 01.

[57] T.K. Hatwar, et al., Development in OLED formulations with improved efficiency and stability, in: Organic Light-Emitting Materials and Devices VIII, SPIE, Nov. 2004, p. 1, https://doi.org/10.1117/12.567418.

[58] H.J. Lee, Y.S. Song, T.K. An, W.K. Choi, S.R. Kim, Ultrasmooth transparent conductive hybrid films of reduced graphene oxide and single-walled carbon nanotube by ultrasonic spraying, Synth. Met. 221 (Nov. 2016) 340–344, https://doi.org/10.1016/j.synthmet.2016.10.012.

[59] Z. Fu, P. Tanninen, J. Keskinen, R. Lev, V. Leminen, M. Mäntysalo, Wear reliability and failure mechanism of inkjet-printed conductors on paperboard substrate, Flexible and Printed Electronics 8 (2) (Jun. 2023), https://doi.org/10.1088/2058-8585/accc9b.

[60] I. Cruz-Cruz, M. Reyes-Reyes, M.A. Aguilar-Frutis, A.G. Rodriguez, R. López-Sandoval, Study of the effect of DMSO concentration on the thickness of the PSS insulating barrier in PEDOT:PSS thin films, Synth. Met. 160 (13–14) (Jul. 2010) 1501–1506, https://doi.org/10.1016/j.synthmet.2010.05.010.

[61] M. Zhang, W. Yuan, B. Yao, C. Li, G. Shi, Solution-processed PEDOT:PSS/graphene composites as the electrocatalyst for oxygen reduction reaction, ACS Appl. Mater. Interfaces 6 (5) (Mar. 2014) 3587–3593, https://doi.org/10.1021/am405771y.

[62] Q. Zhou, S. Chen, M. Zhang, L. Wang, Y. Li, G. Shi, Solution-processed graphene composite films as freestanding platinum-free counter electrodes for bendable dye sensitized solar cells, Chin. J. Chem. 34 (1) (Jan. 2016) 59–66, https://doi.org/10.1002/cjoc.201500609.

[63] S. Yu, P. Yang, B. Wang, N. Zhang, C. Wu, High-temperature resistance of flexible transparent conductive films based on Ag@SnO2 core-shell nanowires for 300 °C, Mater. Lett. 328 (Dec) (2022), https://doi.org/10.1016/j.matlet.2022.133031.

[64] H. Dong, S. Yu, L. Song, X. Wang, C. Wu, Fabrication of high-quality flexible transparent conductive thin films with a Nb2O5/AgNWs/Nb2O5 sandwich structure, Ceram. Int. 48 (11) (Jun. 2022) 15348–15354, https://doi.org/10.1016/j.ceramint.2022.02.068.

[65] S. Yu, et al., Highly stable silver nanowire networks with tin oxide shells for freestanding transparent conductive nanomembranes through all-solution processes, Chem. Eng. J. 446 (Oct. 2022), https://doi.org/10.1016/j.cej.2022.137481.

[66] S. Yu, X. Liu, H. Dong, X. Wang, L. Li, Flexible high-performance SnO2/AgNWs bilayer transparent conductors for flexible transparent heater applications, Ceram. Int. 47 (14) (Jul. 2021) 20379–20386, https://doi.org/10.1016/j.ceramint.2021.04.046.

[67] S. Yu, X. Liu, M. Wu, H. Dong, X. Wang, L. Li, All-solution-processed molybdenum oxide-encapsulated silver nanowire flexible transparent conductors with improved conductivity and adhesion, ACS Appl. Mater. Interfaces 13 (12) (Mar. 2021) 14470–14478, https://doi.org/10.1021/acsami.0c22324.

[68] M. Wu, H. Zheng, X. Li, S. Yu, Highly transparent low resistance ATO/AgNWs/ATO flexible transparent conductive thin films, Ceram. Int. 46 (4) (Mar. 2020) 4344–4350, https://doi.org/10.1016/j.ceramint.2019.10.157.

[69] Y. Zhou, et al., Self-assembled growing ultrathin Ag@NiO core-shell nanowires for stable freestanding transparent conductive colorless polyimide nanomembranes, J. Alloys Compd. 935 (Feb) (2023), https://doi.org/10.1016/j.jallcom.2022.168012.

[70] L. Zhao, P. Yang, S. Shi, X. Wang, S. Yu, Enhanced the thermal/chemical stability of Cu NWs with solution-grown Al2O3 nanoshell for application in ultra-flexible temperature detection sensors, Chem. Eng. J. 473 (Oct) (2023), https://doi.org/10.1016/j.cej.2023.145156.

[71] S. Yu, J. Li, L. Zhao, M. Wu, H. Dong, L. Li, Simultaneously enhanced performances of flexible CuNW networks by covering ATO layer for polymer solar cells, Sol. Energy Mater. Sol. Cell. 221 (Mar) (2021), https://doi.org/10.1016/j.solmat.2020.110885.

[72] S. Yu, W. Zhang, L. Li, D. Xu, H. Dong, Y. Jin, Optimization of SnO2/Ag/SnO2 tri-layer films as transparent composite electrode with high figure of merit, Thin Solid Films 552 (Feb. 2014) 150–154, https://doi.org/10.1016/j.tsf.2013.11.109.

[73] S. Yu, W. Zhang, L. Li, D. Xu, H. Dong, Y. Jin, Transparent conductive Sb-doped SnO2/Ag multilayer films fabricated by magnetron sputtering for flexible electronics, Acta Mater. 61 (14) (2013) 5429–5436, https://doi.org/10.1016/j.actamat.2013.05.031.

[74] S. Yu, et al., Performance enhancement of Cu-based AZO multilayer thin films via graphene fence engineering for organic solar cells, Sol. Energy Mater. Sol. Cell. 183 (Aug. 2018) 66–72, https://doi.org/10.1016/j.solmat.2018.04.008.

[75] S. Yu, L. Li, D. Xu, H. Dong, Y. Jin, Characterization of SnO2/Cu/SnO2 multilayers for high performance transparent conducting electrodes, Thin Solid Films 562 (Jul. 2014) 501–505, https://doi.org/10.1016/j.tsf.2014.04.064.

[76] S. Yu, Y. Liu, H. Zheng, L. Li, Y. Sun, Improved performance of transparent-conducting AZO/Cu/AZO multilayer thin films by inserting a metal Ti layer for flexible electronics, Opt Lett. 42 (15) (Aug. 2017) 3020, https://doi.org/10.1364/ol.42.003020.

[77] S. Yu, L. Li, W. Zhang, H. Dong, D. Xu, Y. Jin, Investigation of low resistance transparent F-doped SnO2/Cu bi-layer films for flexible electronics, Vacuum 102 (2014) 43–47, https://doi.org/10.1016/j.vacuum.2013.10.021.

[78] S. Yu, L. Song, C. Wu, L. Li, Enhanced conductivity and stability of Cu-embedded zinc tin oxide flexible transparent conductive thin films, Ceram. Int. 48 (11) (Jun. 2022) 15925–15931, https://doi.org/10.1016/j.ceramint.2022.02.133.

[79] M. Delfag, et al., Fully printed ZnO-based valency-change memories for flexible and transparent applications, Flexible and Printed Electronics 7 (4) (Dec. 2022), https://doi.org/10.1088/2058-8585/ac9190.

[80] M.N. Tousignant, et al., Poly(ionic liquid) dielectric for high performing P- and N-type single walled carbon nanotube transistors, Flexible and Printed Electronics 7 (3) (Sep. 2022), https://doi.org/10.1088/2058-8585/ac928f.

[81] J. Yoo, S. Li, D.H. Kim, J. Yang, M.K. Choi, Materials and design strategies for stretchable electroluminescent devices, Nanoscale Horizons 7 (8) (May 24, 2022) 801–821, https://doi.org/10.1039/d2nh00158f.

[82] M.K. Choi, et al., Wearable red-green-blue quantum dot light-emitting diode array using high-resolution intaglio transfer printing, Nat. Commun. 6 (May 2015), https://doi.org/10.1038/ncomms8149.

[83] O. Ostroverkhova, Organic optoelectronic materials: mechanisms and applications, Chem. Rev. 116 (22) (Nov. 23, 2016) 13279–13412, https://doi.org/10.1021/acs.chemrev.6b00127. American Chemical Society.

[84] M. Sparks, G.K. Teal, PHYSICAL REVIEW P-N Junction Transistors, 1951.

[85] A. Tavasli, B. Gurunlu, D. Gunturkun, R. Isci, S. Faraji, A review on solution-processed organic phototransistors and their recent developments, Electronics 11 (3) (Feb. 2022), https://doi.org/10.3390/electronics11030316.

[86] A. Tavasli, B. Gurunlu, D. Gunturkun, R. Isci, S. Faraji, A review on solution-processed organic phototransistors and their recent developments, Electronics 11 (3) (Feb. 2022), https://doi.org/10.3390/electronics11030316.

[87] H. Sun, X. Zhang, S. Wang, D. Wang, C. Lee, A high-performance hyperfluorescent device through host optimization, Org. Electron. 125 (Feb. 2024) 106985, https://doi.org/10.1016/j.orgel.2023.106985.

[88] D. Zöller, M. Reiter, D. Abel, Optimization of a vacuum thermal evaporation process through Model-based Predictive Control of the source temperature, in: IFAC-PapersOnLine, Elsevier B.V., 2015, pp. 86–91, https://doi.org/10.1016/j.ifacol.2015.09.164.

[89] K.A. Hussain, G.M. Ali, A. Boubaker, A. Kalboussi, Structural, electrical, and photodetection characterization of a pentacene interdigitated MSM photodiode, J. Electron. Mater. (Feb. 2023), https://doi.org/10.1007/s11664-023-10826-8.

[90] A. Islam, M. Rabbani, M.H. Bappy, M.A.R. Miah, N. Sakib, A review on fabrication process of organic light emitting diodes, in: 2013 International Conference on Informatics, Electronics and Vision, ICIEV 2013, 2013, https://doi.org/10.1109/ICIEV.2013.6572656.

[91] C. Buga, J. C Viana, Optimization of print quality of inkjet printed PEDOT:PSS patterns, Flexible and Printed Electronics 7 (4) (Dec. 2022), https://doi.org/10.1088/2058-8585/ac931e.

[92] C. Príncipe, S.M. Jorge, M. Matos, L. Santos, J. Morgado, A. Charas, 3-oxetanylmethanol as additive to PEDOT:PSS for improved conductivity and water-resistance and applications in ink-jet printed electrochemical transistors, Org. Electron. 125 (Feb. 2024) 106987, https://doi.org/10.1016/j.orgel.2023.106987.

[93] A.L. Roy, C. Beaumont, M. Leclerc, K. Walus, Evaluating polythiophenes as temperature sensing materials using combinatorial inkjet printing, Flexible and Printed Electronics 8 (1) (Mar. 2023), https://doi.org/10.1088/2058-8585/acc07f.

[94] A.L. Roy, C. Beaumont, M. Leclerc, K. Walus, Evaluating polythiophenes as temperature sensing materials using combinatorial inkjet printing, Flexible and Printed Electronics 8 (1) (Mar. 2023), https://doi.org/10.1088/2058-8585/acc07f.

[95] Z. Fu, P. Tanninen, J. Keskinen, R. Lev, V. Leminen, M. Mäntysalo, Wear reliability and failure mechanism of inkjet-printed conductors on paperboard substrate, Flexible and Printed Electronics 8 (2) (Jun. 2023), https://doi.org/10.1088/2058-8585/accc9b.

[96] G. Gramlich, R. Huber, F. Häslich, A. Bhutani, U. Lemmer, T. Zwick, Process considerations for Aerosol-Jet printing of ultra fine features, Flexible and Printed Electronics 8 (3) (Sep. 2023), https://doi.org/10.1088/2058-8585/ace3d8.

[97] D.-H. Cho, et al., Luminance enhancement of top-emitting blue organic light emitting diodes encapsulated with silicon nitride thin films by a double-layer nano-structure, Opt Express 30 (7) (Mar. 2022) 11959, https://doi.org/10.1364/oe.452954.

[98] E. Jiménez-Marín, J. Moreno-Valenzuela, M. Trejo-Valdez, A. Martinez-Rivas, J.R. Vargas-García, C. Torres-Torres, Laser-induced electrical signal filtering by multilayer reduced graphene oxide decorated with Au nanoparticles, Opt Express 27 (5) (Mar. 2019) 7330, https://doi.org/10.1364/oe.27.007330.

[99] Y. Cao, R. Wu, Y.Y. Gao, Y. Zhou, J.J. Zhu, Advances of electrochemical and electrochemiluminescent sensors based on covalent organic frameworks, Nano-Micro Lett. 16 (1) (2024), https://doi.org/10.1007/s40820-023-01249-5.

[100] T. Liu, et al., Hybrid-material-based mirror coatings for picosecond laser applications, Opt Laser. Technol. 171 (Apr. 2024) 110466, https://doi.org/10.1016/j.optlastec.2023.110466.

[101] S.T. Lee, et al., 53.1: invited paper : LITI (laser induced thermal imaging) technology for high-resolution and large-sized AMOLED, SID Symposium Digest of Technical Papers 38 (1) (May 2007) 1588–1591, https://doi.org/10.1889/1.2785622.

[102] R. Geng, A. Mena, W.J. Pappas, D.R. McCamey, Sub-micron spin-based magnetic field imaging with an organic light emitting diode, Nat. Commun. 14 (1) (Dec. 2023), https://doi.org/10.1038/s41467-023-37090-y.

[103] H. Le, A. Minhas-Khan, S. Nambi, G. Grau, W. Shen, D. Wu, Predicting the sheet resistance of laser-induced graphitic carbon using machine learning, Flexible and Printed Electronics 8 (3) (Sep. 2023), https://doi.org/10.1088/2058-8585/acedbf.

[104] S. Rahmati, R.G.A. Veiga, J. Mostaghimi, T. Coyle, A. Dolatabadi, High speed impact and solid-state deposition of alumina particles: a molecular dynamics study, J. Eur. Ceram. Soc. 44 (3) (Mar. 2024) 1733–1747, https://doi.org/10.1016/j.jeurceramsoc.2023.10.017.

[105] K. Mi, X. Ji, S. Xiong, Y. Wang, Molecular layer deposition of conjugated microporous polymers (CMPs) thin films for fast molecular sieving, Sep. Purif. Technol. 332 (Mar) (2024), https://doi.org/10.1016/j.seppur.2023.125783.

[106] A. Bö, P. Urbach, D. Ammermann, W. Kowalsky, Organic Molecular Beam Deposition: Technology and Applications in Electronics and Photonics, 1998.

[107] A.K. Chauhan, P. Jha, D.K. Aswal, J.V. Yakhmi, Organic devices: fabrication, applications, and challenges, J. Electron. Mater. 51 (2) (Feb. 01, 2022) 447–485, https://doi.org/10.1007/s11664-021-09338-0.

[108] A. Mishra, N. Bhatt, A.K. Bajpai, Nanostructured superhydrophobic coatings for solar panel applications, in: Nanomaterials-Based Coatings: Fundamentals and Applications, Elsevier, 2019, https://doi.org/10.1016/B978-0-12-815884-5.00012-0, pp. 397–342.

[109] P.J. Gracie, D. Geetha, H.A. Wahab, I.K. Battisha, Structural elucidation by Raman spectroscopy and analysis of luminescence quenching by the Inokuti-Hirayama model in the Pr3+ doped multi-component silicate photonic films, Opt Laser. Technol. 171 (Apr) (2024), https://doi.org/10.1016/j.optlastec.2023.110406.

[110] M. Singh, P.K. Sahu, S. Sampath, K.N. Jonnalagadda, Fracture toughness of freestanding plasma sprayed yttria stabilized zirconia coatings via in situ tensile experiments, J. Eur. Ceram. Soc. 44 (4) (Apr. 2024) 2499–2511, https://doi.org/10.1016/j.jeurceramsoc.2023.10.074.

[111] L. Vesce, et al., Perovskite solar cell technology scaling-up: eco-efficient and industrially compatible sub-module manufacturing by fully ambient air slot-die/blade meniscus coating, Prog. Photovoltaics Res. Appl. (Feb. 2023), https://doi.org/10.1002/pip.3741.

[112] Y.F. Shen, J. Zhang, C. Tian, D. Qiu, Z. Wei, Slot-die coated large-area flexible all-polymer solar cells by non-halogenated solvent, Nano Res. (Dec. 2023), https://doi.org/10.1007/s12274-023-5861-1.

[113] E. Berger, et al., Recent developments in perovskite-based precursor inks for scalable architectures of perovskite solar cell technology, Sustain. Energy Fuels 6 (12) (May 04, 2022) 2879–2900, https://doi.org/10.1039/d2se00162d.

[114] D.H. Sung, et al., Scalable, roll-to-roll manufacturing of multiscale nanoparticle/fiber composites using electrophoretic deposition: novel multifunctional in situ sensing applications, Compos. Sci. Technol. 245 (Jan) (2024), https://doi.org/10.1016/j.compscitech.2023.110322.

[115] Y. Ma, Roll-to-roll printing trench-like metasurface film for radiative cooling, Light Sci. Appl. 12 (1) (Dec. 2023), https://doi.org/10.1038/s41377-023-01317-w.

[116] K.J. Yoo, J.H. Chang, Comparison of superhydrophobic biodegradable PLA films with fluorine-free hexamethyldisilazane grafted silica and mesoporous silica particles, Results in Materials 21 (Mar. 2024) 100519, https://doi.org/10.1016/j.rinma.2023.100519.

[117] S. William, "Al (12) INTERNATIONAL APPLICATION PUBLISHED under the PATENT COOPERATION TREATY (PCT) (19) World Intellectual Property Organization International Bureau Title: COMPOSITIONS and METHODS for GENERATING MOLECULAR ARRAYS USING OLIGONUCLEOTIDE PRINTING and PHOTOLITHOGRAPHY.".

[118] H.W. Tan, T. Tran, C.K. Chua, A review of printed passive electronic components through fully additive manufacturing methods, Virtual Phys. Prototyp. 11 (4) (Oct. 01, 2016) 271–288, https://doi.org/10.1080/17452759.2016.1217586.

[119] A. Islam, M. Rabbani, M.H. Bappy, M.A.R. Miah, N. Sakib, A review on fabrication process of organic light emitting diodes, in: 2013 International Conference on Informatics, Electronics and Vision, ICIEV 2013, 2013, https://doi.org/10.1109/ICIEV.2013.6572656.

[120] M. Venkatesan, et al., Evolution of electrospun nanofibers fluorescent and colorimetric sensors for environmental toxicants, pH, temperature, and cancer cells – a review with insights on applications, Chem. Eng. J. 397 (Oct. 01, 2020), https://doi.org/10.1016/j.cej.2020.125431.

[121] L. Veeramuthu, et al., Muscle fibers inspired electrospun nanostructures reinforced conductive fibers for smart wearable optoelectronics and energy generators, Nano Energy 101 (Oct) (2022), https://doi.org/10.1016/j.nanoen.2022.107592.

[122] M. Bhrijesh, N. Patel, M. Mrugesh, M. Prajapati, P.M. Patel, OLED: a modern display technology, International Journal of Scientific and Research Publications 4 (6) (2014) [Online]. Available: www.ijsrp.org.

[123] M.-K. Wei, et al., 2004 Optical Society of America OCIS Codes: (080.363) Lenses, (120.4630) Optical Inspection, 2004.