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International Journal of Nanoelectronics and Materials
IJNeaM
ISSN 1985-5761 | E-ISSN 2232-1535

Floating film transfer method for the fabrication of semiconducting polymer-based organic thin film transistor: A mini review

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Received 12 September 2025, Revised 27 October 2025, Accepted 3 November 2025

ABSTRACT

In recent years, the Floating Film Transfer Method (FTM) has gained attention as an innovative approach for fabricating organic thin-film transistors (OTFTs) using organic conjugated polymers. This innovative solution-processing technology provides advantages for the orientation of macroscopic conjugated polymers along with being straightforward processes with encouraging outcomes. Here, we review the recent research on this technology, covering the process mechanism and key variables that affect the mobility of organic thin-film transistors fabricated using this novel method. This review also addresses the ability of FTM to produce uniform thin films of semiconducting polymers on hydrophilic substrates. The review concludes by discussing the limitations and challenges of the FTM.

Keywords: *Floating film transfer method (FTM), Fabrication, Polymer-based semiconducting, Organic thin film transistor (OTFT), Mini review*

1. INTRODUCTION

In light of their benefits in being adaptable for broad applications, conducting polymers have been explored extensively for use in various applications in recent years [1–3]. Nonetheless, several conjugated polymers exhibit both crystalline and amorphous structures, and they struggle to align or orient the molecule to improve its electrical properties. The development of uniform films using a variety of fabrication techniques, independent of molecular orientation, which serves as the foundation for charged transport, has become a bottleneck for the advancement of electronic performance. Consequently, a deposition method that can precisely control the film morphology, crystalline orientation, and molecular/chain ordering of semiconductor domains is desired [4]. Controlling the degree of order in conducting polymer chain organization across multiple length scales is particularly significant [5]. The π-conjugated polymers have already been controlled via a number of ways, including friction-transmitted techniques, liquid crystalline self-organization, Langmuir-Blodgett techniques, and rubbing techniques [6-9]. Recently, numerous researchers have proposed and thoroughly examined a range of procedures aimed at fabricating oriented thin films of conjugated polymers. These procedures involve the use of shear forces to align the conjugated polymer, as well as mechanical rubbing, friction transfer, and strain alignment [9-11]. A thorough understanding of the complex roles of molecule structures, their intermolecular packing, and molecular orientations play important factors in influencing and controlling the final transport properties that are necessary for the development of conducting polymers with high mobility [12]. Even when a process is scaled up within a device, consistency is not guaranteed. While spin-coating is highly effective for film production at the laboratory scale, it is not suitable for roll-to-roll (R2R) processing under ambient conditions, which is essential for scalable and commercially viable manufacturing [13]. Several techniques have been used to adjust the out-of-plane molecule orientation of conducting polymer. These techniques can be divided into two categories, which are external field application and molecular interaction tuning [14]. For the external field application, there is a better option with the friction transfer approach, however, because conducting polymers are drawn up against the substrate, it is difficult to distribute blended polymers uniformly [15], [16] and even using mechanical shear force will result in having a rough surface, and incompatible with hydrophobic surfaces that make it difficult to utilize them in flexible devices [16]. Achieving highly anisotropic charged transport in electronic devices relies on creating straightforward and effective techniques for depositing well-aligned, layered films [17]. By optimizing the π-conducting polymer morphology, macromolecular alignment and better device performance could be achieved [18]. This suggests that, within the molecules of conducting polymer, the hopping rate may vary depending on the intermolecular distance. Carrier transport along the backbone of conducting polymers is significantly more efficient than charge hopping between chains via π–π stacking interactions [19], [20]. This is evidenced by the highest hole mobility being observed along the direction of polymer alignment [μ (0°) = 0.86 cm^2/V·s]. This mobility is over three orders of magnitude greater than the lowest hole mobility, which was measured perpendicular to the polymer alignment direction [μ (90°) = 0.00054 cm^2/V·s] [21]. Due to this, liquid substrates have garnered attention lately because of their capacity to facilitate nanoparticle self-organization in thin films [22], [23], which may enhance the arrangement of molecular order of conducting polymers. Using an eye-catching approach years ago, the solution-floating technique (FTM) was used to successfully construct organic field effect transistor (OFET) [26], which offers an easy and practical way to produce crystalline films of excellent quality [24]. For example, the FTM is an easy and affordable method to create PQT-12 thin films that are well-aligned and smooth [25]. The fabrication method is rather straightforward, where the nanocomposite film floating on a liquid substrate is transferred onto the Si substrate [26] using the stamping method [27]. While this process bears some similarities to the Langmuir Blodgett (LB) method, surface pressure application is not required to form a compact and directed monolayer on the liquid surface [18]. Furthermore, FTM provides a higher-quality film than the widely utilized drop casting and spin coating techniques [27]. The FTM is a relatively novel technique in the fabrication of semiconducting polymer films, particularly for organic thin film transistor (OTFT) applications. Thus, this mini-review aims to first provide an overview of this method with a detailed explanation of its procedure and mechanism. Further, the review allows us to identify existing gaps, limitations and challenges. The review starts by explaining the mechanisms of the FTM, followed by discussing the role of the hydrophilic liquid substrate in floating and oriented conducting polymer thin films. The third section focuses on conducting polymer in terms of solvent parameters and resulting current mobility.

2. FLOATING FILMS TRANSFER TECHNIQUE AND MECHANISMS

Conjugated polymer solution and hydrophilic liquid substrate are the two materials needed for the formation of floating films. When a tiny droplet of polymer solution is deposited onto the surface of a viscous liquid, it initiates the polymer's spreading across the surface, resulting in the formation of floating films (28, 29), as shown in Figure 1(a) [29]. The drop grows quickly and spontaneously because of the Marangoni effect [30]. At the same time, solvents will decrease by evaporation [29]. Within a few seconds, the conjugated polymer chains begin to form aggregated fine structures [13], and then a uniformly thin film formation occurs. This thin film can be easily transferred onto various target substrates using techniques like gentle stamping. As shown in Figure 1(b), the floating mechanism begins when a low-surface-energy organic semiconductor solution is deposited onto a high-surface-energy, hydrophilic liquid substrate [13], [30], [31]. As a result, localized surface tension gradients form at the interface between the materials, causing surface flow to move toward regions with higher surface tension. This process is known as spontaneous Marangoni spreading [30], [32]. The spreading coefficient (S), calculated based on the surface tensions at the interface where the liquid droplet meets the liquid substrate, controls the speed of the spreading flow [33], where S = ɣ1−ɣ2−ɣ12 (ɣ1 and ɣ2 represent the interfacial surface tension between the two solutions and ɣ12 represents the surface tensions of the base and polymer solutions, respectively). Spreading behavior is shown in Figure 1(c). If S is positive, the polymer solution will spread across the surface of the aqueous substrate, forming a uniform polymer film, provided that the surface tension of the base solution (ɣ1) exceeds the combined values of ɣ2 and ɣ12. Without this dispersion, the polymer solution will instead aggregate on the aqueous substrate [13].

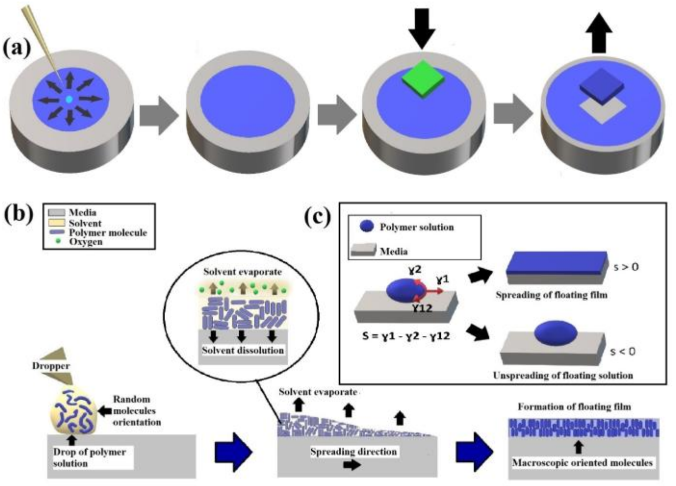

Figure 1. (a) Steps of the formation of a film on hydrophilic liquid substrate: When the polymer solution is dropped onto the medium, it rapidly spreads across the aqueous surface within seconds. Instant drying takes place as the solvents simultaneously evaporate and dissolve, resulting in the formation of a thin solid polymer layer on the medium. This thin film can then be easily transferred to various target substrates, such as by gently stamping them onto the spontaneously spreading (SS) film (b) Illustration of forming floating films with oriented molecules. (c) The behavior of a polymer solution placed on a base solution is determined by the spreading coefficient, S. A positive S value results in the formation of a smooth, continuous polymer film, whereas a non-positive value leads to polymer aggregation.

Floating films can develop either in one or two dimensions. When a droplet of polymer solution is added to the center of a Petri dish filled with a medium, the self-assembling polymer spreads outward in two dimensions, creating circular or elliptical film patterns, as illustrated in Figure 2(a) [25]. On the other hand, Figure 2(b) shows that the droplet will spread mostly in one dimension when it is placed near the border of a circular Petri dish [34]. The polymer's orientation or spreading direction is perpendicular to the direction in which the dropped solution propagates, and the equilibrium between the solidification and spreading speeds may be involved in this orientation [35]. The alignment of the floating film on the liquid surface is influenced by compressive and tensile forces that create shear stress, directing the uniform orientation of macromolecules as the film solidifies, as depicted in Figures 2(c) and 2(d) [35]. Polymer chains that are coordinated can form areas as small as millimeters [5]. The degree of orientation is affected by various factors, including the polymer solution concentration, temperature, and casting conditions like the viscosity of the liquid substrate [35]. The ultimate thickness of the films depends on several factors, including the number of layers applied, the dimensions of the media bath, and both the volume and concentration of the polymer solution used [13].

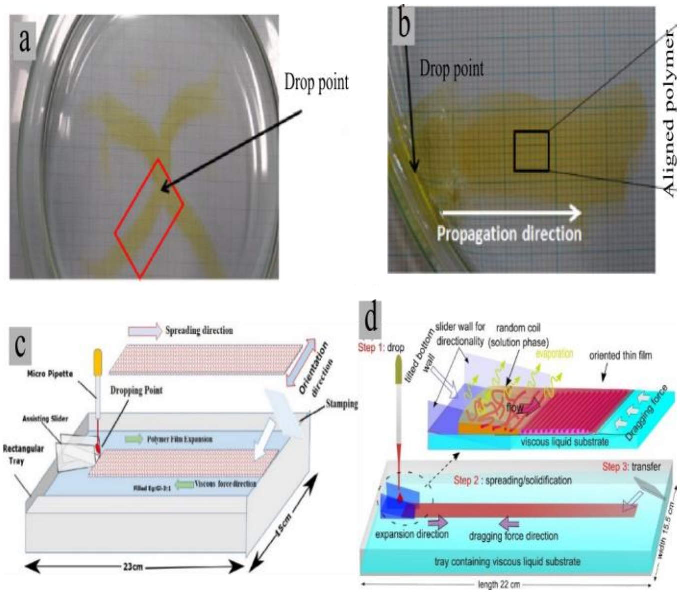

Figure 2. (a) Droplet is placed in the center of a Petri dish, resulting in the formation of circular or elliptical films [34] (b) Drop placed near the border of a circular Petri dish [34] (c) Schematic illustration of the fabrication process for an oriented thin film using a ribbon-shaped floating thin-film method (FTM). [36] (d) Schematic illustration of the fabrication process for ribbon-shaped oriented films using the floating thin-film method (FTM), along with the mechanism responsible for their molecular alignment [37].

3. HYDROPHILIC LIQUID SUBSTRATE TO FLOAT AND ORIENT CONDUCTING POLYMER THIN FILMS

As mentioned in the previous section, in order to obtain floating films of conducting polymer, a hydrophilic liquid substrate is used to cast thin films [38]. The process of film-forming molecular condensation involves the motion of hydrophobic polymeric molecules over a media surface that is soft and hydrophilic. This process is aided by solvent evaporation and results in the induction of orientation in the polymer main chains [25]. The rationale behind the molecular alignment during film formation makes sense when one considers that the hydrophilic liquid substrate's viscosity of the media acts as a compressive external force to prevent the propagation of hydrophobic polymer solutions once they begin [18]. This will slow down the spreading of polymeric molecules and support the molecular orientation of the polymeric molecules. A study shows that the liquid substrate affects the orientation characteristics in floating films by using a variety of low-viscosity liquid substrate combinations, such as distilled water and ethylene glycol and high-viscosity liquid substrate combinations, such as glycerol. The results showed that the viscosity of the liquid substrate strongly influenced the orientation intensity (indexed by dichroic ratio (DR)), which in turn affected the solidification speed of the floating film materials [38]. Films with greater orientation form when the viscosity of the liquid substrate exceeds a certain threshold, however, if the viscosity continues to increase beyond this point, the degree of orientation begins to decline. The optimal orientation was achieved using a mixture of ethylene glycol and glycerol with a dynamic viscosity of 29.56 centistokes, resulting in a dichroic ratio (DR) of 6.8 for the NR-P3HT film at 30 °C above the casting temperature [18]. Besides viscosity, the surface energy of the liquid components plays a crucial role by controlling the interactions between the outer molecular layers of the hydrophilic liquid and the hydrophobic polymer chains, which is believed to impact the spreading behavior of the polymer solution [18]. Given that the hydrophobic polymer solution remains constant, it seems that the surface energy of the liquid phase controls the extent of the polymer's spreading [18]. Because surface energy is effectively surface tension per unit area, adjusting the liquid phase composition to vary surface tension offers a way to control both the spreading and the resulting thickness of floating films [18], as shown in Figures 3(a), (b) and (c). Since surface tension changes in this context in the sequence of water < ethylene glycol < glycerol, the binding force between glycerol and polymer will be the strongest, resulting in the slowest floating film propagation [18]. In this process, the solvent volatilizes while the polymer solution constantly concentrates, resulting in the formation of a lyotropic liquid-crystal phase [18], which encourages the self-alignment of macromolecules [18]. In the dynamic floating transfer method, the synergistic action of the lyotropic liquid-crystal phase and the compressive force causes the polymer alignment in the tangential direction [25]. The liquid substrate's viscosity essentially acts as an external dragging force for the polymer solution to spread, which influences the polymer's self-organization and orientation [18]. In a study, Tripathi et al. discovered a ribbon-shaped film of PQT produced a very large area [(20 cm (L) × 2 cm (W)], highly oriented thin floating films on a hydrophilic liquid substrate with a tiny amount drop of 25 μl of PQT solutions. This results in floating films that are 15 cm long [37]. This suggests that the FTM technology may be applied to vast areas since it may be used to manufacture huge orientation films of polymer and use them for the appropriate applications. Given that a single drop (~20 μl) of polymer solution can produce around 100 OFETs, the ribbon-shaped FTM method demonstrates efficient material utilization during thin film fabrication [36]. Table 1 shows the ratio of mixture for hydrophilic liquid substrates on the mobility performance of OTFTs.

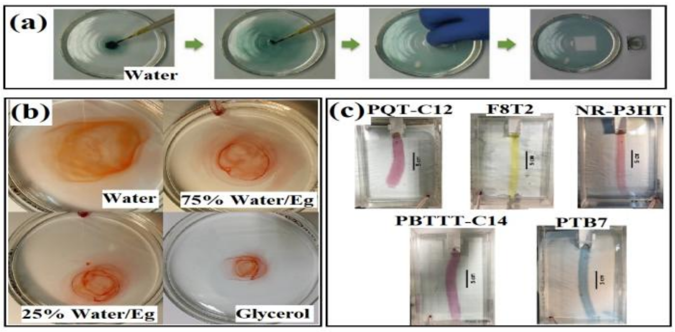

Figure 3. (a) Schematic illustrations depicting the formation of a spontaneously spreading (SS) bulk heterojunction (BHJ) film on a water surface and its subsequent transfer onto target substrates [13]. (b) Pictures depict a floating film formed in a Petri dish measuring 7 cm in diameter [38]. (c) Photographs show thin films made from different conjugated polymers (CPs), produced using the ribbon-shaped floating thin-film method (FTM) under consistent casting conditions: a liquid substrate of ethylene glycol and glycerol mixed in a 3:1 ratio, a casting temperature of 60 °C, and a polymer concentration of 1% (w/w) dissolved in chloroform [36].

Table 1. Ratio of hydrophilic liquid substrates and its impact on the mobility performance of OTFTs

Hydrophilic Liquid Substrate	Ratio	Organic Semiconductor		Casting temperature	Mobility ($\mathrm{cm^2\,V^{-1}\,s^{-1}}$)	References
EG:G	3:1	NR-P3HT		- 25 °C	3.4×10^{-3} -	[17], [35]
DI:G	1:2	RR-P3HT		42 °C	-	[35]
G	1:0	PBTTT-C14		70 °C	-	[35]
DI	1:0	PBTTT-C14		NA	2.3×10^{-2}	[39]
EG:G	2:1	PQT-C12		25 °C	-	[35]
EG:G	3:1	PQT-C12		60 °C	5×10^{-2}	[36]
EG:G	3:1	F8T2		60 °C	1.05×10^{-3}	[36]
EG:G	3:1	NR-P3HT		60 °C	4.2×10^{-3}	[36]
EG:G	3:1	PBTTT-C14		60 °C	7.5×10^{-3}	[36]
EG:G	3:1	PBTTT-C14		55 °C	1.1×10^{-1}	[39]
EG:G	3:1	PTB7		60 °C	1.9×10^{-4}	[36]
EG:G	1:1	PQT-12		NA	8.77×10^{-3}	[27]

*EG: Ethylene glycol, DI: Deionized Water, G: Glycerol

4. CONDUCTING POLYMER FOR FLOATING FILM TRANSFER

Due to the π-orbital overlap throughout the conjugated polymer backbone, conducting polymers have highly anisotropic optical and electrical properties, including absorption, emission, and conductivity [21]. Conducting polymers are the preferred material for floating films because they exhibit a lyotropic liquid-crystalline (LC) phase [40], which allows for the development of molecular alignment and self-assembly properties through external stimulation [31]. Therefore, FTM is expected to play a vital role as a fast and straightforward technique for creating oriented thin films by leveraging the lyotropic liquid crystal phase transition properties of conjugated polymers [35]. The self-assembled and better-aligned PQT-12 film, as opposed to the spin-coated films, is responsible for the increased mobility in the FTM-based OTFT [32]. Studies have been conducted on conjugated polymers with LC properties, such as poly(2,5-dinonyloxy-pphenylenevinylene) [40], (9,9-dioctylfluorene-co-benzothiadiazole) (F8BT) [41], cyclopentadi-thiophene-based polymer [42], oly(bis(5-(dodecyloxy)-2-nitrobenzyl) 1-(5-(2,5-difluoro-4-(thiophen-2-yl)phenyl)-thiophen-2-yl)-4H-cyclopenta[c]thiophene-5,5(6H)-dicarbox-ylate) (CP1-P) [31], PCDTPT/PCDTBT [42], [43], [44], P(NDI2OD-T2) [45] and P3ATs [46]. Most conjugated polymer for FTM was chosen from the polythiophene family [35], including poly(3-hexylthiophene) (P3HT) [26], poly (3, 3000-dialkylquaterthiophene) (PQT-12) [47], [48], regioregular poly(3-hexylthiophene) (RR-P3HT) [35], poly[2,5-bis(3-tetradecylthiophen-2 yl)thieno[3,2-b]thiophene] (PBTTT-C14) [35] and Poly(3,3′′′-didodecyl-quarterthiophene) (PQT-C12) [35]. Using polarised UV–Vis spectral mapping and the fabrication of bottom-gated organic field-effect transistors (OFETs) from various locations, orientation features and charge transport anisotropy are able to be examined [49].

The choice of solvent for the conducting polymer significantly influences its orientation behavior on the hydrophilic liquid substrate. Recent research has concentrated on casting conducting polymer films with high-boiling-point solvents like chlorobenzene (boiling point: 131 °C) onto hydrophilic liquid substrates to improve device performance and facilitate the production of multilayer thin films [13], [50]. The slow evaporation rate of the high boiling point solvent will allow the macromolecules to self-organize on the liquid substrate and produce isotropic floating films [39]. Because of the flexible properties of floating films, selecting the right solvent (high or low BP) during the conjugated polymer solution production process is a crucial step that affects the thin film's growth mechanism. The low boiling point solvent of poly[2,5-bis(3- tetradecylthiophen-2-yl) thieno [3,2-b]thiophene] (PBTTT-C14), which has a rather strong molecular orientation and a high optical DR of 6.5, is an excellent example of macroscopic orientation with mobility of 1.1×10^{-1} cm/Vs [39]. Furthermore, it demonstrates that the rapid solvent elimination caused by the spontaneous spreading process may prevent oxygen from fully infiltrating the film through the residual solvent [13]. This may result in the disruption of the π-conjugated backbone through cleavage and the insertion of oxygen into the polymer's carbon–carbon double bonds [13]. The disruption that took place could be one of the factors that helped the conjugated polymer during the floating films process to exhibit isotropic behavior. The increase in π-conjugation length in low boiling point film compared to high boiling point film is supported by the absorption spectroscopic measurements [17], [51] that enhance π-orbital delocalization [52]. Compared to films made with high boiling point solvents, the out-of-plane x-ray diffraction (XRD) patterns indicate that low boiling point films promote a more extended lamellar structure of PBTTT-C14 exhibiting an edge-on orientation. This behavior leads to the observed field-effect mobility after the fabrication of OFETs, with a preference given to low boiling point solvents rather than those with higher boiling points [39]. Ultrafast solvent evaporation during the spontaneous spreading process enables the rapid formation of a dense and tightly packed thin film [13]. Conversely, a very high initial polymer concentration at the air/liquid interface combined with rapid solvent evaporation can raise the nucleation rate, leading to the formation of numerous small crystallites [53], [54]. This impact may be lessened under ideal conditions if there is an adequate concentration of conjugated polymer. In contrast, it has been observed that the OTFT device made with the P3HT channel layer utilising the solution floating method and toluene solvent has better electrical properties than the devices made with the solvents tetrahydrofuran (THF) and chloroform [24]. This may result from the slow evaporation rate of a high boiling point solvent that gives sufficient time for the molecules to assemble in order orientation before the solvent completely leaves the floating films and solidifies.

The concentration of conducting polymer solution has been suggested to range from 0.1 to 1% (w/w) due to the likelihood of a high nucleation rate at the air/liquid interface [18]. Many studies employed concentrations of 1% (w/w) and below from their respective conjugated polymers, as shown in Table 2. It has been reported that excessive conjugated polymer concentration causes too fast solvent evaporation and polymer solidification, which prevents the polymers from expanding and reduces the amount of uniform floating film that can form on the liquid substrate [18]. On the other hand, the limitations of raising the conjugated polymer concentration and its impact on electrical characteristics have not yet been discovered. A study discovered that at a film thickness of 10 nm, field-effect mobility is highly repeatable, and the film thickness may be easily adjusted by increasing the conducting polymer content [49].

Table 2. Conducting Polymer with Various Solvent and Concentration

Conducting Polymer	**Solvent**	**Concentration**	**Amount Drop of Organic Polymer**	**Thickness (nm)**	**Mobility ($cm^2 V^{-1} s^{-1}$)**	**Ref.**
NR-P3HT	NA	1 % (w/w)	25 µl	20 nm	3.4×10^{-3}	[17]
NR-P3HT	NA	1 % (w/w)	25 µl	20 nm		
poly[2,5-bis(3-tetradecylthiophen-2-yl) thieno [3,2-b]thiophene] (PBTTT-C14)	Chloroform	1 % (w/w)	-	25 nm	1.1×10^{-1}	[39]
RR-P3HT	Chloroform	0.3 (wt. %)	30 µl	35 to 40 nm	1.07×10^{-4}	[29]
PQT-C12	Chloroform	1 % (w/w)	20 µl	-	5×10^{-2}	[36]
F8T2	Chloroform	1 % (w/w)	20 µl	-	1.05×10^{-3}	[36]
NR-P3HT	Chloroform	1 % (w/w)	20 µl	-	4.2×10^{-3}	[36]
PBTTT-C14	Chloroform	1 % (w/w)	20 µl	-	7.5×10^{-3}	[36]
PBTTT-C14	Chloroform	1 % (w/w)	-	-	1.1×10^{-1}	[39]
PBTTT-C14	Chlorobenzene	0.5 % (w/w)	-	-	2.3×10^{-2}	[39]
PTB7	Chloroform	1 % (w/w)	20 µl	-	1.9×10^{-4}	[36]
P3HT	Toluene	10 mg/ml	30 µl	-	2.27×10^{-2}	[26]
PQT-12	Chloroform	5 mg/ml	15 µl	~20 nm	8.77×10^{-3} (FTM)	[27]

					2.96×10^{-3} (SC)	
P(NDI2OD-T2)	Chloroform	1 % (w/w)	-	-	0.19	[55]

Some of the factors that influence the mobility performance of conducting polymer are intermolecular interactions, which will affect packing motif, crystallinity, and self-assembly elements that are critical to the charge transport characteristics of conducting polymer [42]. The crystallinity of FTM films of RR-P3HT is more intense and crystalline, with a greater grain size of 19 nm for FTM films compared to 16 nm for spin-coated films [56]. Another study shows that the full width at half maximum (FWHM) of RAMAN spectra of the poly[[4,8-bis[(2-ethylhexyl)oxy]benzo[1,2-b:4,5-b′] dithiophene-2,6-diyl][3-fluoro-2-[(2-ethylhexyl) carbonyl]thieno [3,4-b]thiophenediyl]] (PTB7) of the C=C mode narrowed, indicating the higher degree of molecular order of the PTB7 chains in the floating film. Additionally, the intensity ratio between the C–C and C=C vibrational peaks (IC–C/IC=C) in the floating film rose from 0.46 to 0.49 [13]. Even though FTM film forming under casting conditions is being optimized, the composition of conjugated polymers themselves varies [35]. For example, slow growth of the crystalline domain in RR-P3HT is known to facilitate the evolution of lower vibronic modes since it leads to the production of fibrous crystalline domains [57]. The elongation of the conjugation length along the polymer backbone is primarily indicated by the growth of the low vibronic mode [35]. Nevertheless, it was discovered that the RR-P3HT exhibits a weak orientation even with the best casting condition adjustment [35]. Meanwhile, NR-P3HT was more orientated than RR-P3HT because NR-P3HT has less interlocking, which allows for free sliding, while RR-P3HT's zipper effect from interdigitating limits the sliding action of nearby backbones [17][35][58][59]. For instance, because of the zipper effect caused by their alkyl side-chain arrangement, RR-P3HT strongly had relatively low orientation [35]. These findings imply that RR-P3HT's high regioregularity prevents additional polymer chain orientation enhancement. Polarized absorption measurements of PQT-C12 and PBTTT-C14 films show significant optical dichroism, with DR values of 6.4 and 5.1, respectively—substantially exceeding the DR value of 1.5 observed in RR-P3HT films [35]. To offer a solution to this problem, Syafutra et al. combine the poor orientational ability of conjugated polymer with the high orientational ability of conjugated polymer in order to overcome the weak orientation of conjugated polymer [15]. Their findings showed that blending poly(9,9-di-noctylfluorenyl-2,7-diyl) with the host polymer poly(3,3′′′-didodecylquaterthiophene) (PQT) led to an increase in the polymer's dichroic ratio (DR) by about two to four times. However, raising the concentration of the guest polymer in a blend can lead to phase separation, and the resulting morphology may vary depending on the individual component ratios and the overall polymer concentration [15]. Information on how blended films of this solution via FTM affect charge transport and mobility performance is still missing. Although thin film charge mobility (average ~ $\times 10^{-4}$ – $\times 10^{-2}$ cm^2/Vs) is still low for the FTM method, there is still potential for improvement through internal and external approaches. Altering the backbone length, conjugated units, and regioregularity of the polymer, along with incorporating nanocarbon materials into the conjugated polymer matrix, can potentially enhance charge transport efficiency [26]. Additionally, nanocarbon materials can function as conductive pathways linking the crystalline regions within the semiconductor film, facilitating quicker charge transport and thereby enhancing the transistor's effective mobility [60], [61]. Research indicates that blending P3HT with electrochemically exfoliated graphene (EEG) slightly enhances the mobility of OTFTs, increasing it from 0.0227 cm^2/V·s for pure P3HT to 0.0391 cm^2/V·s for a P3HT/EEG mixture at a mass ratio of 100:10 [26]. The shoulder peak seen at 600 nm is linked to interchain π-π* transitions taking place within the P3HT chains [62]. Additionally, the peak underwent a red shift as a result of charge transfer interactions between the materials, increased chain mobility, and better crystalline alignment between the π-π interacting EEG surface and the thiophene chains of P3HT [26]. Moreover, the P3HT/EEG nanocomposite film exhibited a notable enhancement in the intensities of the (002) and (100) diffraction peaks. This indicates that an optimal amount of EEG in the composite can encourage stronger intermolecular interactions and improve crystallinity [26]. The presence of large P3HT crystalline domains induced by EEG causes the P3HT/EEG nanocomposite film to display more pronounced worm-like structures and a higher root mean square (RMS) roughness of 2.45 nm, in contrast to the P3HT film, which has an RMS roughness of 1.91 nm [63],[64]. This further confirms that, compared to pure P3HT, the P3HT/EEG composite exhibits a more interconnected crystalline morphology facilitated by the 2D structure of EEG, improving the linkage between grain boundaries within the P3HT domains. Charge carrier transport in the active layer is complicated by the smaller domains of the active channel layer, which is only made up of long polymer chains devoid of EEG sheets. This issue can be resolved by incorporating a large-area, highly conductive EEG that acts both as a conductive bridge facilitating charge carrier transport in the active channel layer and as a promoter of enhanced crystallinity [65]. The distinctive flexibility and solution-process ability of conducting polymers must be preserved in order to boost their mobility and facilitate the industrialization of organic electronic devices [26]. It has been shown that the supramolecular arrangement within the thin film transferred onto a solid substrate is affected by the conditions under which the stable floating layer forms at the air-water interface [66]. A study showcases the scalability of this approach by using a custom-designed roll-to-roll (R2R) process to transfer the floating film from the water surface onto a large plastic substrate [13]. Table 3 shows a comparison of the mobility of conducting polymer thin films fabricated using FTM and spin coating methods.

Table 3. Comparison of Charge Carrier Mobility in Conducting Polymer Thin Films Prepared by FTM and Spin Coating Techniques

Conducting Polymer	Mobility, cm^2/Vs (FTM)	Mobility, cm^2/Vs (Spin Coating)	Ref.
NR-P3HT	3.40×10^{-3}	2.10×10^{-5}	[17]
PQT-12	8.77×10^{-3}	2.96×10^{-3}	[27]
PQT-C12	5.00×10^{-2}	6.7×10^{-4}	[36]
F8T2	1.05×10^{-3}	2.0×10^{-4}	[36]
NR-P3HT	4.2×10^{-3}	1.0×10^{-5}	[36]
PBTTT-C14	7.5×10^{-3}	5.2×10^{-3}	[36]
PTB7	1.9×10^{-4}	1.1×10^{-4}	[36]

5. LIMITATIONS AND CHALLENGES OF FTM

As mentioned earlier, two key factors influence the orientational capability of thiophene-based polymers: (i) the liquid crystalline behavior of the material, and (ii) the ability of the side chains to interdigitate, which facilitates free movement of the polymer backbones in solution. In the FTM process, this enables the solution to spread and dry at the same time [15]. There is still uncertainty regarding how much it may impact mobility performance. The limitations and challenges are listed below:

1) The orientation ability is determined by the type of the conducting polymer.

2) The performance and properties of conducting polymers are still affected by oxygen penetration in thin films, which is still a difficulty.

3) The influence of solvents on the nucleation and growth rates of conducting polymers remains underexplored. Furthermore, limited studies have investigated the effects of employing dual solvents or mixing solvents with varying boiling points on P3HT thin films fabricated via the FTM method

4) In the FTM process, a custom-built slider was used to create a large film area (14–20 cm in length) by guiding the film's spreading direction, though the exact angle of the slider was not reported in the studies.

5) The P3HT/EGG20 sample, which had the highest EGG content, could not function well as the OFET devices' active channel layer due to EGG aggregation in the nanocomposite solution [26].

6. CONCLUSION

In this mini-review, we have provided an overview of the FTM as applied to the fabrication of macroscopic orientation semiconducting polymer films for OTFTs. FTM has emerged as a versatile and effective technique for producing uniform, high-quality polymer films, which are critical for the performance and reliability of OTFTs. Compared to conventional methods, FTM offers several advantages, including the ability to create diverse films with controlled thickness and reduced surface defects. Its relatively simple setup and process also make it an attractive option for scalable production. Moreover, the technique allows for the deposition of films onto different types of substrates, enhancing its applicability in flexible organic electronics. As demonstrated above, applying this strategy improves mobility and charge transport performance. On the other hand, certain advantages and disadvantages are discussed in the literature regarding how the fabrication processes impacted the organic electronic device architecture. However, FTM offers a novel approach that has just lately surfaced to address the issue with the current technology. To be sure of this method, the novel approach to the production of organic thin films might provide the answer to the riddle that contemporary conventional technology is unable to solve.

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For the future perspectives and emerging trends, recent advances in the floating film transfer method (FTM) indicate promising directions for next-generation organic thin-film transistors (OTFTs). Current trends include integrating FTM with roll-to-roll (R2R) printing for large-scale production, exploring hybrid systems combining conjugated polymers with 2D nanomaterials (e.g., graphene, MoS_2), and improving film uniformity through solvent engineering and surface energy tuning. Future research should also focus on enhancing environmental stability, achieving higher charge mobility (>1 $cm^2/V\cdot s$), and understanding interfacial dynamics during film formation. Furthermore, combining in-situ characterization techniques can provide valuable insights into molecular ordering and film evolution for industrial applications in flexible electronics and sensors.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support received by Malaysia Ministry of Higher Education, Fundamental Research Grant Scheme, Grant Numbers: FRGS/1/2023/STG07/UKM/02/5

AUTHOR CONTRIBUTIONS

Nur Zuraihan Abd Wahab contributed to the conceptualization and methodology of the study, prepared the original draft of the manuscript, and participated in the critical review and editing process. Muhammad Mahyiddin Ramli and Ahmad Ghadafi Ismail were responsible for reviewing and revising the manuscript content. Abdullah Abdulhameed provided supervision, as well as critical review and editorial input on the manuscript. Roslina Mohd Sidek, Suhaidi Shafie, Zhiwei Zhaof, Ali H. Reshak, and Mohd Nazim Mohtar contributed to the review and revision of the manuscript.

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