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Analysis of Three Techniques in Constrcting OFET

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Abstract. The Organic Field-Effect Transistor (OFET) boasts several salient features including flexibility, reduced power consumption, and enhanced biocompatibility, positioning it as a pivotal component in the advancement of flexible electronics, wearable technologies, and medical electronic devices. Despite its considerable attributes, the OFET's widespread adoption is hindered by inherent limitations, notably its low carrier mobility. Consequently, there is a concerted effort within the research community to augment OFET performance. This manuscript delineates three predominant methodologies employed in the fabrication of the organic semiconductor layer integral to OFETs: spin-coating, dip-coating, and inkjet printing techniques. For each method, a comprehensive analysis of its underlying principles, procedural intricacies, and performance metrics—such as carrier mobility, cost-efficiency, crystal quality, and applicability scope—is presented. Additionally, empirical instances employing these techniques are meticulously examined to furnish a clearer comprehension of their practical implications. This paper contribution aims to equip future investigators with the knowledge to judiciously select appropriate techniques for their research endeavors, thereby facilitating the evolution of OFET technology.

Keywords: OFET, spin-coating, dip-coating, inkjet printing.

1. Introduction

The flexibility of organic field effect transistors (OFET) have let OFET-based integrated circuits get rid of hard substrates, which have played an important role in flexible electronics, wearable devices, medical electronics and other fields [1]. However, due to progress of these industries in recent years, present products can no more meet the demands. Developing flexible organic integrated circuits with high performance, biocompatibility, low cost and low power consumption has become an industry trend [2]. To improve the performance of the whole circuit, one good way is to improve the structure and preparation strategy of OFET from the source.

The major challenges for OFET to be in widely use are how to enhance the performance of OFET and how to produce in large scale. Compared with traditional field effect transistors (FET), present OFETs' organic semiconductor layers' carrier mobility is inherently smaller [3]. Secondly, defects and grain boundaries in the organic semiconductor layer of OFET will result in a sharp increase in resistance which affects the overall performance. There are several directions that scientists are working hard to improve the performance of OFETs and adjusting the growth conditions, crystal quality and crystal morphology of organic crystals to improve the overall OFET performance is one of the most feasible methods.

Here this paper introduces 3 techniques that are widely used in constructing high performance OFETs which are spin-coating techniques Dip-coating techniques and inkjet printing techniques. Each technique's procedures, range of application, index including carrier mobility, cost, crystal quality are detailly explained. Examples are also included to better demonstrate these techniques. This paper can help researchers choose proper technique to improve the performance of OFET by adjusting the growth process of organic semiconductors.

2. Spin-coating techniques

Spin-coating is a widely used thin film preparation method and especially suitable for preparing organic semiconductor thin film in OFETs. It has been widely used in multiple situations including chip production, laboratory and production development [4].

The first step is to prepare the substrate. Silicon substrates and Glass substrates are widely used as hard substrates while Polyester film (PET), polyimide (PI), polyvinyl alcohol film (PVA) are often used as flexible substrates especially in constructing flexible OFETS. In this case, silicon or glass serves as the bottom support of the polythiophene film. The surface of the substrate needs to be cleaned and treated to ensure the film's adhesion and consistency. The next step is to prepare the solution. It usually contains the desired polymer or material, solvent, and possible additives. The selection of polymer or small molecule-weight semiconductor depends on the desired film material characteristics and application. While solvent is chosen based on the compatibility of the solvent, substrate and the requirements of the coating process.

After preparing the gate electrodes, gate medium layer and the source and drain electrodes, drop prepared solution on the centre of the substrate. Then make the solution evenly distributed on the surface of the substrate by rotating the substrate. Rotation speed and rotation time are important parameters that affect the quality and performance of the film, usually vary around 1000 rpm. The thickness and crystallinity of the film can be controlled by adjusting the rotation speed and rotation time. After completing the coating process, the system still needs to be rotated for a while to remove remaining solvent. The evaporation of the solvent can be accelerated by heating or inert air flow. In some cases, further drying or heating is applied if the crystallization and solidification of the film needs to be promoted [5].

As a widely applied method in OFET construction, spin-coating have some significant advantages. The first advantage is that spin-coating is a researcher-friendly method, which means that researchers can master this technique with little training. Spin-coating method is also one of the easiest ways to produce single thin film as it does not need any high-energy process [6].

Second advantage is that spin-coating works very well in coating small and flat substrates. By rotating, solution will evenly distribute on the surface of the substrate. During the process of spin-coating, the thickness of the applied layer is directly proportional to the viscosity of the substance being coated, raised to the power of two, and is inversely proportional to the square root of the workpiece's rotational velocity [7]. As a result, by changing the character of the solution including intensity, viscosity, rotation velocity, components, researchers can produce thin films with different thickness (nanometer to micrometer scale). Thickness is given by $t = kp^2/w^{1/2}$, where k=spinner constant, typically 80-100, p represents viscosity, w=spinner rotational speed in rpm/1000.

Due to the rotation of substrate, thin films can be formed rapidly with little drying time. And also because of the high rotation speed, thermal process after deposition is not always necessary as the flow generated by high-speed rotation can dry the thin film. The drying process is highly uniform.

However, there are also some limitations. Major one is that spin-coating only works in small substrates. As the size of the substrate increases, the speed of the rotary coating is limited, making it difficult to obtain a thin and uniform film layer, and the amount and cost of solution will increase. The biggest disadvantage comes from the use of solution is low efficiency, in the total amount of lolution applied each time, only 2 to 5% of the solution left on the substrate as a useful film layer. The schematic of the OTFTs and its atomic force microscopy (AFM) image of the C8-BTBT thin film on a PVA dielectric layer is shown in figure 1.

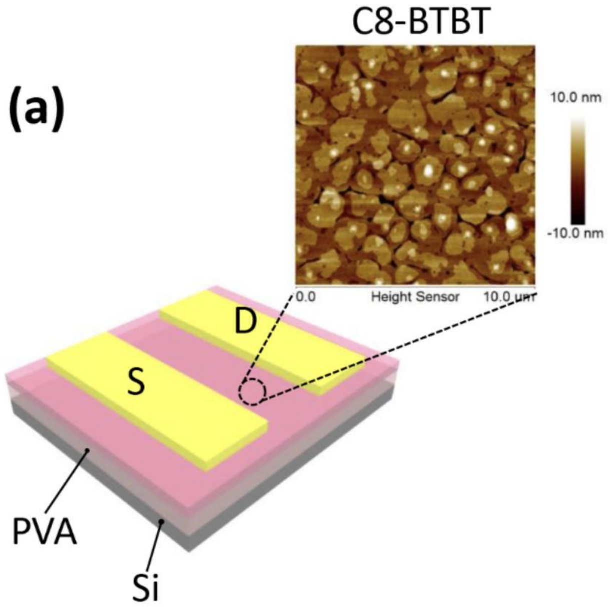

Figure 1. Schematic of the OTFTs and its atomic force microscopy (AFM) image of the C8-BTBT thin film on a PVA dielectric layer [8]

Spin-coating typically results in organic semiconductor films with relatively high charge carrier mobility. This is due to the formation of uniform films, reducing the impact of grain boundaries and defects on charge carrier transport, thus enhancing carrier mobility. Thin films often exhibit random molecular orientation. Although process parameters can influence molecular orientation to some extent, compared to methods like vacuum evaporation, spin-coating generally yields films with poorer molecular orientation. So, it may not be a good way to produce large area of single crystal semiconductor.

In one study, Ren, H., et al successfully fabricated ultra-thin flexible organic thin-film transistors based on C8-BTBT thin films by spin-coating [8]. The thickness of coming about device is only about 320 nanometers, making the device highly adherent and suitable for three-dimensional curved surfaces. The ultra-thin C8-BTBT OTFTs showed a high mobility of reaching 4.36 $cm^2\ V^{-1}\ s^{-1}$ and its switch current ratio exceeding 10^6. The researchers also investigated the effect of polyvinyl alcohol (PVA) solution concentration on the device performance and found that spin-coating C8-BTBT thin films in a 6 wt% PVA solution yielded the best device performance.

3. Dip-coating techniques

Dip-coating is also widely used in constructing the organic semiconductor layer, especially in recent years when researchers are studying the patterning of organic semiconductor [4].

Dip-coating is a technique that deposit thin films on the surface of the substrate by pulling substrates from prepared solution. It mainly has followed several steps. First step is to prepare and clean the substrate, usually silicon or glass while flexible substrates are also appropriate for these techniques. Second step is to put the substrate in the prepared solution which can be either a dissolved solution containing the desired material or a solution with suspended solid particles and ensure the substrate is fully covered with solution [9]. By controlling the dip speed and dip depth, the liquid is fully covered and evenly adhered to the surface of the substrate. The liquid coated substrate is then slowly withdrawn from the solution. In this process, surface tension and gravity will make the liquid evenly covered on the surface of the substrate and thus form a film. Finally, the substrate coated with solution will then be placed in the appropriate environment, so that the solvent gradually volatilizes. Solution can be dried naturally at room temperature or may need to be heated on a hot table to speed up drying [10].

In some cases, researchers may need to repeat above steps several times to get a thicker organic semiconductor layer and other procedures may also come after like baking, annealing or other chemical treatment to further improve the performance and quality of the film [3].

There are several reasons for the widely use of Dip-coating in constructing semiconductor layer in OFET. One is it has simple operation which does not require complex equipment and high-precision process conditions. Since the substrate is completely impregnated in the coating solution, the dip coating method usually produces a coating with high coverage and uniformity. This facilitates the formation of a uniform and continuous film on surface of the substrate [11]. Also, it can easily prepare large areas of coating, suitable for situations where large areas of substrate need to be covered. This makes dip coating method has certain advantages in mass production. Compared to other coating methods, the dip coating method is less costly because it does not require expensive equipment and consumables. Meanwhile, it does not require high temperature or high-pressure conditions and can be carried out at room temperature.

However, there are also some drawbacks. Due to the surface tension effect of the dipping process, the crystal structure formed by the film may not be orderly enough, thus affecting the performance [12]. The diagram of dip-coating based source/drain orientation assembly of carbon nanotubes is shown in figure 2.

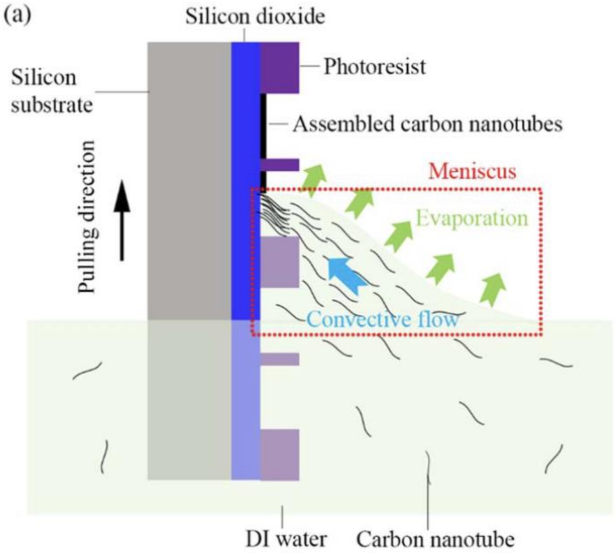

Figure 2. Diagram of dip-coating based source/drain orientation assembly of carbon nanotubes [13]

One research carried by Chai, Z., et al reports a scalable and controllable method for the directional assembly of ordered crystalline C8-BTBT thin films [13]. During the experimental process, the substrate is vertically put into the solution and then pulled out at a controlled speed, achieving directed crystal growth along the stretching axis through a combination of the linear three-phase interface (gas-liquid-substrate) and uniaxial stretching. By altering two key parameters: the extending speed of the substrate and the concentration of the arrangement, self-aligned stripe designs with flexible thickness and morphology can be gotten, with sizes coming to the level of square centimeters. OFETs were constructed by C8-BTBT lean movies collected beneath diverse conditions, coming about in a high field-effect carrier mobility of reaching 3.99 $cm^2 V^{-1} s^{-1}$. Because of its exceedingly adaptable crystalline film arrangement, this drenching coating directional gathering strategy may be a perfect choice for making novel electronic gadgets.

Another study carried by same group prepared solution-processed OFETs on both silicon and flexible transparent polyethylene terephthalate (PET) substrates by using carbon nanotubes as the source or drain electrodes and C8-BTBT to construct semiconductor layer [14]. The experimental process is as follows: firstly, CNT source/drain electrodes were assembled on silicon substrates using immersion coating directional assembly process, followed by the assembly of C8-BTBT thin films to complete the preparation of OFETs. Secondly, on PET substrates, a 2.5 μm thick photoresist (AZ 2020) was spin-coated as the gate dielectric layer using a solution method, followed by UV radiation cross-linking and then baking on a hot plate to prepare the photoresist dielectric film. The prepared OFET devices exhibited typical p-type behavior. However, their carrier mobility reached only 0.2 cm^2 V^{-1} s^{-1}. The experimental results demonstrated the successful fabrication of OFET devices through the preparation of directionally assembled carbon nanotube source/drain electrodes and C8-BTBT thin films. This fabrication process has advantages such as low cost, ease processing, scalability to wafer level, and good compatibility with different substrates, making it highly suitable for next-generation electronic and sensor applications. However, the trade-off is the relatively low carrier mobility. The schematic illustration of C8-BTBT film by dip-coating is shown in figure 3 [14]. The C8-BTBT film shows a stripe pattern, and the stripe formation mechanism is shown in (b) and (c).

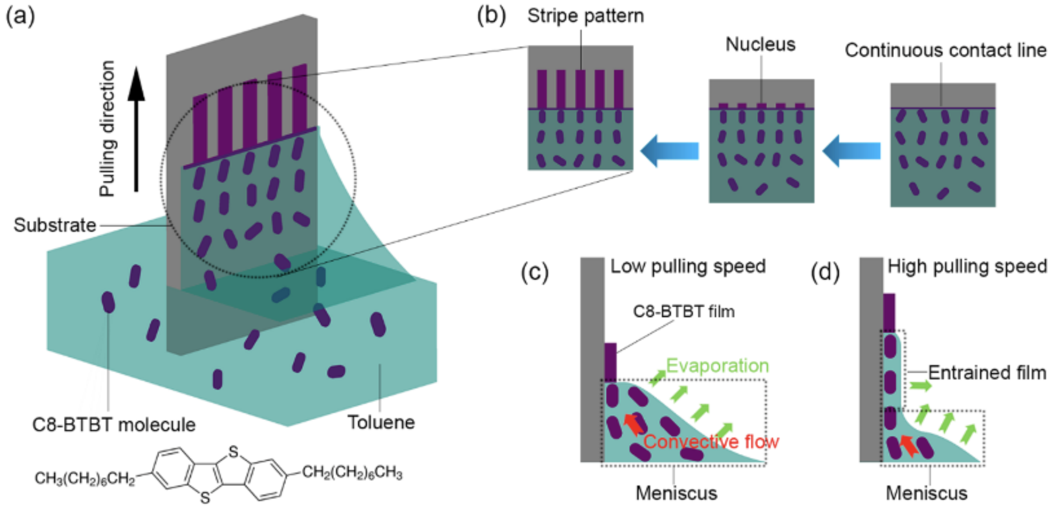

Figure 3. Schematic illustration of C8-BTBT film by dip-coating [14]

4. Inkjet printing techniques

Inkjet printing technology is a relatively newer method for thin-film fabrication, emerging commercially after spin-coating and CVD. With growing requirements for high-throughput, low-cost, flexibility, and customization, inkjet printing gradually gained attention as a promising thin-film fabrication technique. It is particularly suitable for large-area, flexible, and customized fabrication processes [4, 9].

Constructing organic semiconductor layers using inkjet printing usually have 4 steps. Which are preparation of Ink, inkjet Printing, drying and solidification and Post-treatment (optional). Ink containing the organic semiconductor material dissolved or dispersed in a suitable solvent will be first formulated. Then ink properties will be adjusted including viscosity, surface tension, and particle size distribution for optimal printing performance. By using the inkjet printer to print precise droplets of the organic semiconductor ink onto the substrate surface in a controlled manner. Film's thickness and uniformity can be adjusted by changing printing parameters such as droplet size, spacing, and printing speed. The deposited ink droplets will then dry and solidify on the substrate surface. By controlling drying conditions such as temperature and humidity researchers can optimize film formation and prevent defects. In order to have better film quality and electrical properties, additional treatments can be performed such as annealing or surface modification to improve. And last step is to conduct characterization tests to evaluate the performance of the printed organic semiconductor layer, including electrical conductivity, charge carrier mobility, and film morphology [6, 15].

In most cases, ink would dry rapidly, which means that it is hard for molecules have an ideal crystallization process. Thus, the performance of the organic semiconductor thin film including carrier mobility will not be excellent due to the poor crystal quality and existence of grain boundaries.

However, in resent research, organic semiconductor thin film with high crystallization is no more impossible by using special methods like using patterned substrate to make precursor grow in a settled direction thus getting single crystal [16].

Inkjet printing have some outstanding advantages that make it popular among researchers. One is that Inkjet printing is a digital manufacturing technology that allows for customized design and rapid prototyping with high flexibility which means that it can easily achieve patterning itself without the aid of lithography in 100 micrometer scale or with the aid of lithography in 10 nanometer scale [6]. Meanwhile, compared with the traditional preparation method, inkjet printing needs lower cost and has higher efficiency, and can quickly prepare a large area of film, which is suitable for large-scale production [17]. Also, it will be easier to prepare organic semiconductor thin film on flexible substrates compared with other two method.

However, its drawbacks cannot be negligible. The surface of the inkjet printing film is often not smooth and uniform, and there may be big grains or uneven surface topography affecting the performance and stability of the device [18]. Furthermore, a rapid printing method combined with the use of unsuitable solvents can often result in the formation of inferior quality crystals. This approach may also give rise to the undesirable "coffee-ring" phenomenon, characterized by a noticeably thicker center compared to the surrounding areas [19]. The diagrams of organic single-crystal thin films by Inkjet printing is shown in figure 4.

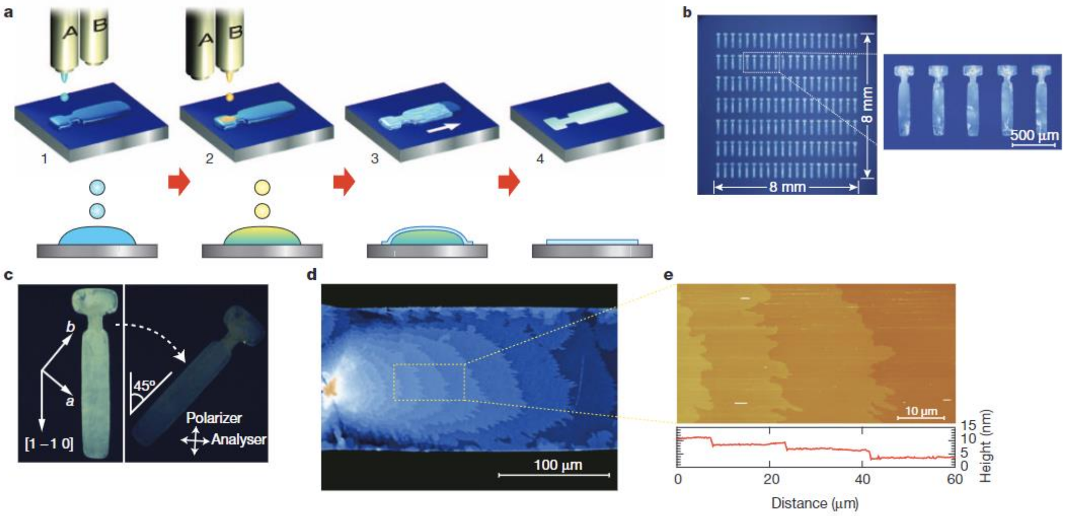

Figure 4. Diagrams of organic single-crystal thin films by Inkjet printing [20]

Growing high performance semiconductor layer by single crystal is one of its mainstreams. One research carried out by Minemawari, H., et al utilized a method that combines anti-solvent crystallization technology with inkjet printing to prepare highly crystalline organic semiconductor thin films on amorphous substrates [20]. Solution containing active semiconductor components were first Inkjet printer of a on the upper surface of predefined hydrophilic regions. Within one second, a specific pattern was printed, followed by the printing of 6 drops of anti-solvent. Tiny floating bodies formed on the surface of the droplets, acting as nuclei for crystal growth, gradually growing into larger floating bodies. These floating bodies eventually covered the entire surface of the droplets, forming single-crystal or polycrystalline thin films. As the solvent slowly evaporates, the film became smoother, ultimately achieving a thickness of about 30-200 nanometers.

Experimental results indicate that organic semiconductor thin films printed using this method exhibit high crystallinity and achieve high charge carrier mobility. Taking the organic semiconductor C8-BTBT as an example, the average charge carrier mobility reaches up to 16.4 $cm^2 V^{-1} s^{-1}$. The schematic of OSSCs by inkjet-printing is shown in figure 5.

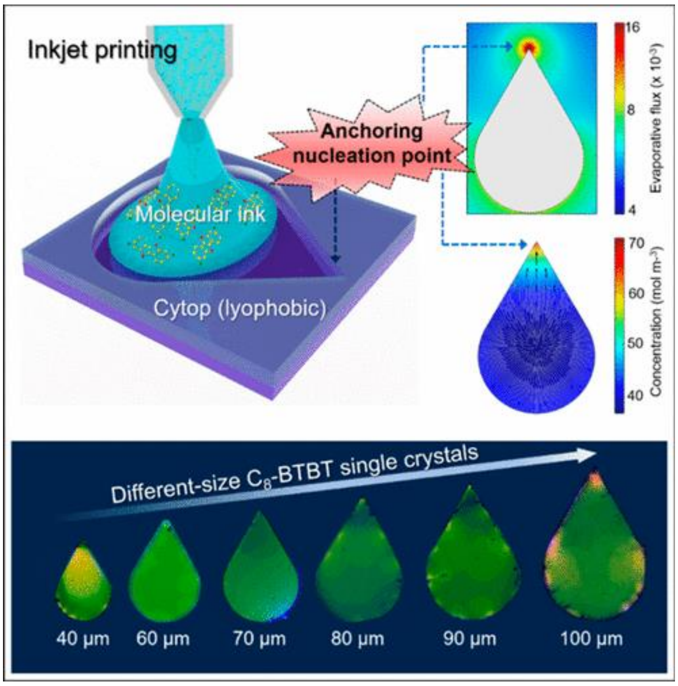

Figure 5. Schematic of OSSCs by inkjet-printing [21]

Another study carried by Ren, X., et al achieved high-throughput inkjet printing of organic semiconductor single crystals by controlling the nucleation process through the manipulation of specific microscale patterns [21]. Researchers designed a contact line with a tear-shaped micro-pattern, and by adjusting the curvature, they successfully positioned molecular nucleation at the vertices of the topological structure, forming individual crystal nuclei, followed by the growth of organic semiconductor single crystals. DBTT was used as the material in this method, and ordered growth of DBTT single crystals was successfully achieved. Through this approach, researchers patterned the growth of DBTT organic field-effect transistor arrays, obtaining groundbreaking results with an average mobility of up to 12.5 $cm^2 V^{-1} s^{-1}$.

5. Conclusion

Spin-coating technique is capable of coating the entire substrate surface quickly and can achieve relatively uniform films by controlling spin speed and time on various types of substrates. However, there are also some disadvantages including hard to realize large-area coating, very low material using efficiency and hard to prepare patterned organic semiconductor layers.

Dip-coating technique is especially used when coating complex-shaped substrates or substrates with uneven surfaces which means it is especially suitable to prepare patterned organic semiconductor layers. It has relative low cost and uniformity can be controlled when precise film thickness is required. Disadvantages are that a long period of time is need and uniformity is hard to control on large substrates.

Inkjet printing is quite a new technique, which can directly construct micrometer level semiconductor patterns, which is widely used in the fabrication of OLED displays or organic photovoltaic devices. It is especially suitable for large-scale production of electronic devices where customization and digital control are preferred. It also generate minimized material waste, as inkjet printing only deposits ink where needed, reducing material consumption. Disadvantages like limited material selection which means only solutions with high viscosity and low surface tension are suitable for inkjet printing, high cost and long time-consumption when dealing with large-area applications.

As a result, when choosing the technique for growing organic semiconductors, factors such as product requirements, production scale, and equipment cost need to be considered comprehensively. Choosing the most proper technique will make OFET have most ideal performance.

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