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Review

Alignment and patterning of organic single crystals for field-effect transistors

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ABSTRACT

Organic field-effect transistors are of great importance to electronic devices. With the emergence of various preparation techniques for organic semiconductor materials, the device performance has been improved remarkably. Among all of the organic materials, single crystals are potentially promising for high performances due to high purity and well-ordered molecular arrangement. Based on organic single crystals, alignment and patterning techniques are essential for practical industrial application of electronic devices. In this review, recently developed methods for crystal alignment and patterning are described.

1. Introduction

Organic semiconductors have aroused increasing attentions in recent years due to their outstanding performances and potential applications in electronic devices, such as organic field-effect transistors (OFETs) [1–6], organic solar cells [7], organic light-emitting diodes (OLEDs) [8]. These devices exhibit numerous advantages compared with inorganic semiconductor counterparts, including flexibility, low-cost and low-temperature processability [4,9–11]. Of all those fabricated organic electronic devices, OFETs are critically fundamental components for integrated circuits, primarily act as switches and signal-processing elements for practical applications, like radio-frequency identification tags and active matrix displays [2,3,12]. Normally, device performances have extremely close relationships with crystalline structures and imperfections of the crystalline structures always account for poor performances [13,14]. Imperfections such as grain boundaries and molecular disorders not only influence the quality of obtained crystalline morphologies, but also hinder the charge transport by scattering charge carriers. Therefore, single-crystal organic semiconductors, which perform excellent properties with the highest order as well as purity, lead to superior charge carrier mobility among organic electronic materials [15–18]. So far, many methods have been proposed to fabricate organic devices based on organic single crystals [19–21].

Despite of all the advantages above, the scale-up of organic single crystals for practical applications is still challenging since the growth orientation and location as well as alignment of single crystals are usually difficult to control. While large-scale industrial applications with high integration demand high uniformity and minimal cross-talk between neighboring devices [22], it is of extreme importance to pattern single crystals at well-designed locations. The development of patterning and alignment techniques is indispensable for the realization of integrated devices, and will undoubtedly facilitate the progress of single-crystal organic semiconductors for practical applications [23]. Over the last decade, many efforts have been devoted to promote various strategies for growing organic semiconductor molecules into well-aligned patterns as well as ordered arrays with the positions and locations under control, precisely. In this article, we review the recent progress of this research topic [24–36].

2. Crystal alignment

Charge carrier transport in organic single crystals has been demonstrated to be anisotropic [37–39]. Alignment of the crystals in a unidirectional fashion is, hence, necessary to achieve the potentially uniform OFET performance. Concentration and/or

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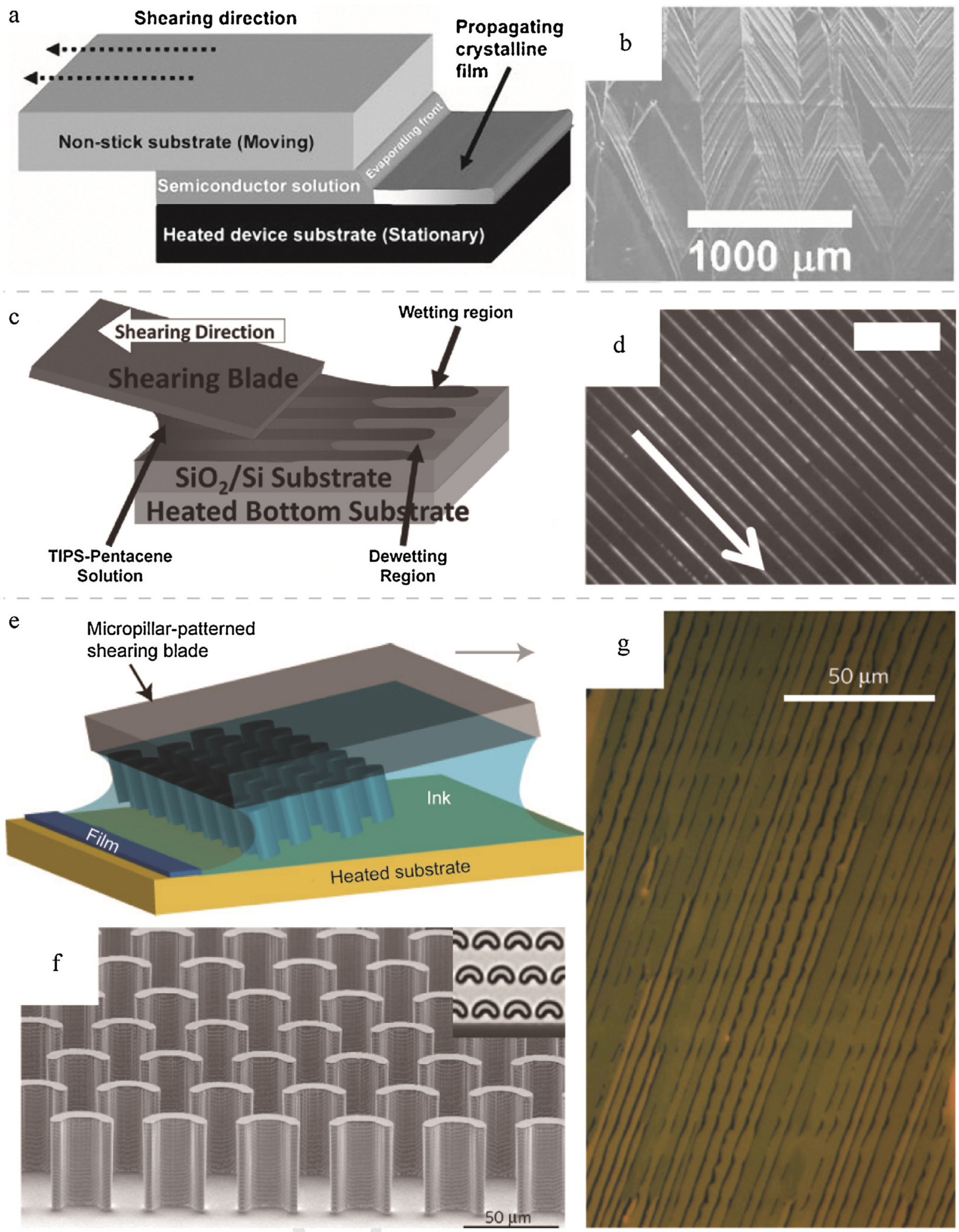

Fig. 1. (a) Schematic illustration of solution-shearing. (b) Bright-field optical microscopy (OM) image of prepared TMS-4T film, showing elongated crystalline structures. (c) Schematic illustration of substrate patterning and crystalline thin film growth by solution-shearing method. (d) Cross polarized optical microscopy (CPOM) image of solution-sheared TIPS-pentacene thin films with 0.5 μm patterned line width. The scale bar is 25 μm and the white arrow indicates the shearing direction. (e) Schematic illustration of solution-shearing using a crescent micropillar-modified blade. The arrow shows the shearing direction. (f) Scanning electron micrograph (SEM) of the micropillar-patterned blade. (g) CPOM image of TIPS-pentacne thin film with micropillars.
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temperature gradients as well as tilted substrates have been used to control the crystallization direction [27,29,40–46]. Solution-shearing and droplet-pinned crystallization (DPC) method are two typical and facile approaches to align organic crystals.

As depicted in Fig. 1a, a solution of organic material was sandwiched between the heated device substrate, which can be modified to improve wetting, and the shearing substrate, which can be modified to cause dewetting. As the upper substrate moved steadily, the front of solution evaporated and created nuclei followed by additional organic molecules continuously flowing towards nuclei and self-organizing to form aligned structures. After solution-shearing, uniform crystalline film of quarterthiophene (TMS-4T) were deposited parallel to the direction of the shearing movement and extended over the entire heated substrate (Fig. 1b) [47]. The shearing rate is a crucial parameter since fast shearing rates lead to very thin films and moderate crystalline structures. By optimizing the shearing speed, the conjugated backbones of 6,13-bis(triisopropylsilylethynyl)pentacene (TIPS-pentacene) can be packed more tightly, resulting in reduced π–π stacking distance from 3.33 Å to 3.08 Å [48]. Since the introduced lattice strain within the crystal lattice effectively enlarged orbital overlap between component molecules, the charge carrier