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Control of droplet morphology for inkjet-printed TIPS-pentacene transistors

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ABSTRACT

We report on methods to control the morphology of droplets of 6,13-bis(triisopropyl-silylethynyl) pentacene (TIPS-PEN), which are then used in the fabrication of organic thin film transistors (OTFTs). The grain size and distribution of the TIPS-PEN were found to depend on the temperature of the droplets during drying. The performance of the OTFTs could be improved by heating the substrate and also by changing the relative positions of the inkjet-printed droplets. In our experiments, the optimum substrate temperature was 46 °C in air. Transistors with the TIPS-PEN grain boundaries parallel to the current flow between the source and drain electrodes exhibited charge carrier mobilities of 0.44 ± 0.08 cm^2/V s.

1. Introduction

There is increasing academic and industrial interest in the solution-fabrication of organic thin film transistors (OTFTs). Significant advantages over other methods of manufacture include the low cost and the relatively low temperature of the processing, which is suited to plastic substrates [1–3]. Inkjet printing is one of the most promising solution-based methods for the controlled deposition of organic semiconductors. The process is non-contact, maskless and provides very efficient use of material [4,5]. Many electroactive organic compounds can be deposited as thin films in this manner. However, the electrical performance of OTFTs based on inkjet printing is generally not as good as that exhibited by transistors in which the organic semiconductor is deposited in other ways, e.g. by thermal evaporation. This is related to the relatively poor morphology of the inkjet-printed films.

Pentacene is a high performance p-type organic semiconductor. This compound is not very soluble and is generally processed using thermal evaporation. In contrast, the derivative 6,13-bis(triisopropyl-silylethynyl) pentacene (TIPS-PEN) has been developed for solution processing. This can exhibit a charge carrier mobility as high as 1.8 cm^2/V sec [6,7] when deposited by spin-coating and possesses good environmental stability [8]. However, for the reason noted above, the carrier mobility in inkjet-printed TIPS-PEN OTFTs is invariably less than that noted for devices produced by spin-coating. The molecular ordering of TIPS-PEN strongly depends on the nature of the droplets. For example, mixed solvents can generate Marangoni flow (which may be produced by gradients in either temperature or chemical concentration at an interface) together with a natural convective flow, resulting in crystal grains that depend on the vapor pressure of the different solvents. In this study, we have used TIPS-PEN as the active semiconductor material and optimized the inkjet printing process using a single solvent. To improve further the performance of the OTFTs, we have investigated the influence of substrate heating and grain orientation with respect to the source and drain electrodes.

2. Experiments

Test chips, which contained 40 identical OTFTs, were fabricated to investigate the statistical variation in the electrical properties of the devices. The structure is shown in Fig. 1. The individual transistor architecture was based on a bottom contact configuration, in which the source and drain electrodes were located beneath the semiconductor. The channel length (L) and width (W) were 20 μm and 310 μm, respectively. The fabrication procedure, undertaken in a class 1000 clean room, was as follows. First, an aluminum layer with 100 nm thickness was evaporated on a glass substrate and patterned by photolithography to provide the gate electrodes. Polyvinylphenol (PVP) was then spin coated on the gate electrode to form the gate dielectric layer; the details of this step can be found in the literature [9]. To form the source and drain electrodes, Au was evaporated onto the PVP layer and patterned

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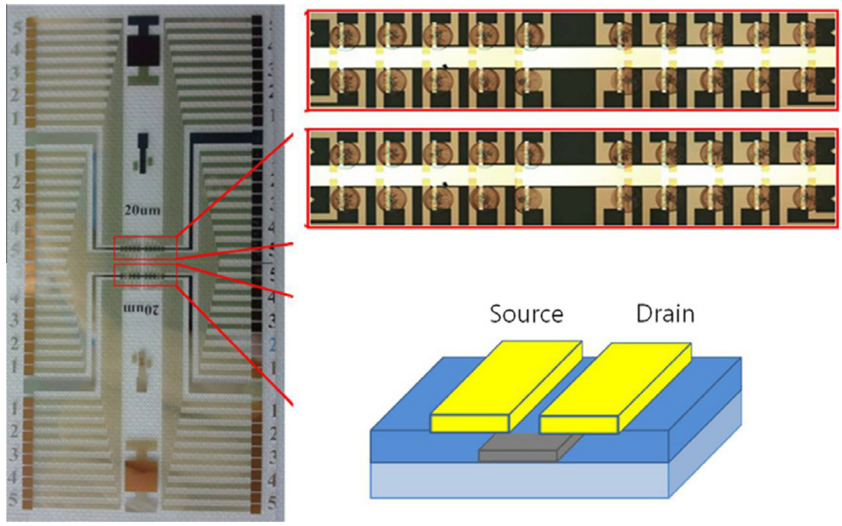

Fig. 1. Microscope image of test chip and the structure of OTFT.

by a lift-off process. The semiconductor solution consisted of 3 wt% TIPS-PEN mixed with anisole (from Aldrich); the solution was stirred for 3 h. The concentration of 3 wt% was optimized in the previous study so that it was unchanged in this experiment. Finally, the TIPS-PEN solution was jetted onto the source and drain electrodes using an UNIJET UJ2400 inkjet printer.

In our experiments, the droplets were printed onto the channel region of the transistors at 20 °C (room temperature), 36, 46 and 56 °C in air. The transfer and output characteristics of the OTFTs were measured by a semiconductor parameter analyzer (Keithley SCS-4200). All the electrical measurements were undertaken in ambient air condition. The charge carrier mobility was calculated in the saturation regime.

3. Results and discussion

3.1. Substrate temperature

Several effects are involved in the drying of an inkjet-printed droplet, as indicated in Fig. 2. These include the outward convective flow to compensate for the evaporation loss at the edge of droplet and the inward Marangoni flow due to the gradient of the surface tension. Marangoni flow occurs along the droplet surface from the edge to the center and counterbalances the convective flow. The result is a recirculation of material in the droplet [10,11]. Depending on which force is dominant, either a ‘coffee stain’ or a uniform layer may be obtained. It has been suggested that the transformation from an inkjet-printed droplet of liquid to a solid takes place in three steps [12]. First, the liquid evaporates with a fixed line of contact to the substrate. During this stage, material is transported from the center of the droplet to its edge by convective flow produces the classic ‘coffee stain’ pattern. Subsequently, the droplet shrinks with a receding contact line. Finally, the contact line again becomes pinned to the surface as a result of the high viscosity of the remaining liquid. This third stage defines the morphology of the central region of the inkjet-printed droplet.

It was found that printing the TIPS-PEN at room temperature from the anisole solvent resulted in crystals accumulating in the vicinity of the droplet contact line; this is shown in the optical microscope image of Fig. 3(a) and takes the form of the coffee stain pattern. On application of heat during drying, the more rapid evaporation of the solvent significantly reduced this effect and the crystals were shifted from the edge to the center of the droplet. These effects are depicted in the schematic diagram shown in Fig. 2, which indicates a possible mechanism for the formation of kinetically aligned TIPS-PEN crystals during the drying process.

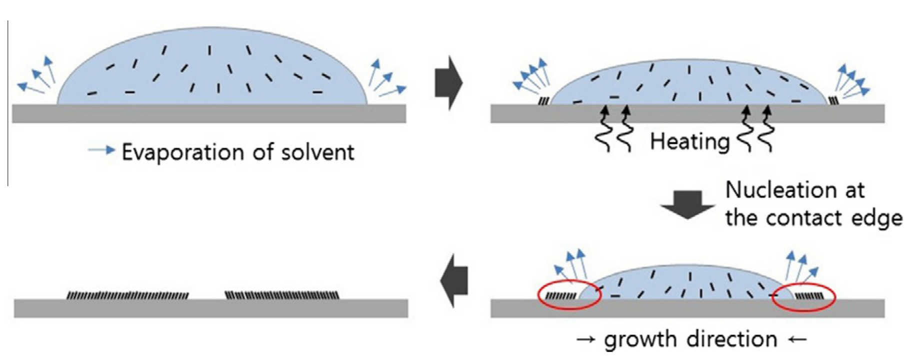

Fig. 2. A schematic depiction of a possible mechanism for the formation of TIPS-PEN crystal. The crystals were grown from the edge to the central droplet by substrate heating.