Thin-film transistor electrical performance of hybrid MoS$_2$-P3HT semiconductor layers

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Abstract—The hole carrier field-effect mobility of hybrid molybdenum disulfide (MoS$_2$) nanoparticles suspended in poly(3-hexylthiophene) (P3HT) thin film transistor (TFT) was found to be enhanced by nearly $10^3$ compared to P3HT-only TFTs. The improvement in the hole charge transport was found to be a function of the concentration of MoS$_2$ in P3HT with high MoS$_2$ concentrations resulting in an increase in the on-current of the device. Both the hybrid and conventional polymeric TFTs exhibited a threshold voltage of 2 V and an on-off ratio of $>10^5$.

I. INTRODUCTION

Organic semiconductors have been widely used for solution-based fabrication such as spin-coating and printing due to their good solubility in conventional solvents. The benefit of solution processing is its cost-effective, large area, non-vacuum, low-temperature fabrication and particularly, its effectiveness in additive processes [1], [2]. Solution-processed electronics include sensors, displays, and photovoltaics [3]–[8]. Meanwhile, thin-film transistor (TFT) is a fundamental component of electronics. The field-effect mobility and the threshold voltage of TFT are the most important factors to assess the device performance [9]. Whereas, when it comes to channel materials for organic TFTs (OTFTs), as compared to inorganic materials, organic materials have inherent limitations such as low field-effect mobility [10].

A novel approach to overcome this limitation is through an organic/inorganic hybrid semiconductor composite, which we expect to use as ink for printed OTFT. Through this approach, the limitations, such as low field-effect mobility and non-soluble process of both the organic and inorganic materials can be overcome. Previous works of blending organic semiconductors with various inorganic materials such as carbon nanotubes [11], [12], zinc oxide (ZnO) nanorods [13], titania (TiO$_2$) nanorods [14], and graphene [15], [16] are reported. However, the main challenges of these works are low on/off ratio less than three orders of magnitude [12], [13], [15], and huge threshold voltage shift, over $-20$ V [11], [12], [14]. To address these problems, we newly suggest a solution processible molybdenum disulphide (MoS$_2$) suspended in poly(3-hexylthiophene) (P3HT). The nanocomposite solution was used for an active channel layer of TFTs to fabricate a bottom gate TFT by spin-coating (Fig. 1). The dependence on the device performance on the different concentrations of MoS$_2$ is presented.

II. MATERIALS

P3HT is well known and widely studied in last few decades as p-type polymeric semiconductor which is used in OTFT since it is quite stable in ambient and has high mobility [17], [18]. Fig. 2a shows the molecule structure of P3HT. It has long-range intermolecular side-chain and it forms inter-chain interaction as a highly ordered pi-stacked polymer which is shown in Fig. 2b. High pi-stacking interactions are directly associated with the crystallization of P3HT which attributes to efficient charge transport. Organic semiconductors follow hopping mechanism due to the high density of impurities and traps which are known as localized sites [19]. To increase the charge transport, the polymer should have high molecular ordering. It can be achieved by surface treatment method using self-assembly monolayer (SAM) such as hexamethyldisilazane (HMDS). The wettability of the substrate reduces after HMDS treatment which affects the molecular ordering of polymers at dielectric/polymer interface [20], [21]. The interface between insulator and organic semiconductor is known to have a high density of trap states. The low surface energy of HMDS-treated dielectric surface enables polymer to be more crystallized which result in fewer interface states [19].

One of the transition metal dichalcogenides materials (TMDCs), MoS$_2$ has been attracted great attention due to its various superior electrical and optical characteristics. Distinct characteristics of MoS$_2$ include high field-effect mobility on its two-dimensional state, good flexibility, transparency, and high-air stability thanks to its atomically thin layer. There were many attempts to use it in a soluble process by exfoliating bulk material into thin nanoflake. Layered MoS$_2$ is coupled via weak van der Waals force between interlayers and the layers can be separated by exfoliation which is shown in Fig. 2c. In this work, MoS$_2$ presents as nanoparticles in the P3HT channel layer to improve overall electrical characteristics of OTFTs.
in the channel layer effectively helps the charge transport of organic film of P3HT.

The hole field-effect mobility of each device in the saturation regime was calculated by the gradual-channel approximation:

$$I_{DS} = \frac{W C_{ox} \mu}{2L} (V_G - V_T)^2$$

where $C_{ox}$ and $\mu$ are the gate oxide capacitance and field-effect mobility, respectively. $V_G$ and $V_T$ are gate voltage and threshold voltage, respectively. The threshold voltage, $V_T$, was determined using a linear fit to the square root of drain current versus gate voltage. These calculated values are summarized in Table 1. The field-effect mobility also continuously increases with increasing concentration of MoS$_2$. The field-effect mobility of MoS$_2$-P3HT nanocomposite TFTs (P3HT/1.0 wt% MoS$_2$) is $1.43 \times 10^{-2}$ cm$^2$/V-s which is five times higher than the baseline device. The mobility of P3HT film based on our baseline TFT is $2.60 \times 10^{-3}$ cm$^2$/V-s. This measurement result shows that the fabricated TFT has a smaller variation of the threshold voltage and better the on/off ratio compare with previous studies [11]–[15].

According to the previous study, reported hole mobility in monolayer sheets of MoS$_2$ was 96.62 cm$^2$/V-s [22]. Hence, we expect that due to the much higher hole field-effect mobility of MoS$_2$ compared to P3HT film, MoS$_2$ works as a high transport region within the organic film. From the energy band diagram of the device which is shown in Fig. 5, both valance band edge of MoS$_2$ and HOMO level of P3HT can be found around 5.2 eV. Moreover, Au has a high work function of 5.1 eV which is suitable with the HOMO level of P3HT. We find that MoS$_2$ and Au have the proper energy level for hole transport and injection.

The output characteristics of the baseline device and nanocomposite TFT (P3HT/1.0 wt% MoS$_2$) are shown in Fig. 4. The drain current was measured as a function of drain voltage ($V_{DS}$) with different gate bias voltages ($V_G$) under dark conditions. The range of drain bias voltages are swept from 0 V to -50 V in a step of -2 V. Both output curves depict the modulated drain current by an applied drain voltage.

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**Fig. 2** (a) Schematic illustration of conjugated P3HT (b) π-π stacking of conjugated P3HT in edge-on direction (c) Atomic structure of bi-layer MoS$_2$. Each monolayer of MoS$_2$ is coupled via weak van der Waals force between the layers and the distance is 6.5 Å.

**Fig. 3** Transfer characteristics of MoS$_2$-P3HT nanocomposite TFTs with different concentrations of MoS$_2$ in the forward scan.

**Fig. 4** Output characteristics of nanocomposite (circle) and baseline (square) TFTs.
Furthermore, in the linear regime, the drain current depicts a linear I-V characteristic indicating these devices are unaffected by the source/drain contact resistance. In the saturation regime, it was observed that nanocomposite TFT has a higher on-state current than P3HT-only TFT. These results provide experimental evidence of the MoS₂ enhancing the charge transport characteristic of the organic TFT device performance.

Meanwhile, the increase of the concentration of MoS₂ in the organic film does not increase proportionally when comparing different MoS₂ concentrations suspended in P3HT. We speculate that the existence of inorganic nanoparticles may hinder the molecular ordering of P3HT film, which will be the subject of future studies to find optimum concentrations of MoS₂ in the composite film.

![Energy band diagram](image)

**TABLE I**

| DEVICE | \( \mu_{sat} [\text{cm}^2/\text{V-s}] \) | \( V_T [\text{V}] \) | \( I_{on}/I_{off} \) |
|--------|---------------------------------|----------------|-----------------|
| P3HT-only | 2.60×10^{-3} | 2 | 1.71×10^{5} |
| P3HT/0.3 wt% MoS₂ | 4.50×10^{-3} | 2 | 1.77×10^{5} |
| P3HT/0.5 wt% MoS₂ | 8.60×10^{-3} | 2 | 2.31×10^{5} |
| P3HT/0.8 wt% MoS₂ | 1.28×10^{-3} | 1 | 1.02×10^{5} |
| P3HT/1.0 wt% MoS₂ | 1.43×10^{-3} | 1 | 9.05×10^{4} |

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