Abstract—We demonstrate fabrication of bottom-gate/top source-drain contacts for p-channel (small molecule) organic field-effect transistor (OFET) using pentacene as an active semiconductor layer and silicon dioxide as gate dielectric. The device exhibits a typical output curve of a field-effect transistor (FET). Furthermore, analysis of electrical characterization was done to investigate the source-drain voltage ($V_{ds}$) dependent mobility. The mobility which calculated using MATLAB simulation exhibited a range from 0.0234 to 0.0258 cm$^2$/Vs with increasing source-drain voltage (average mobility was 0.0254 cm$^2$/Vs). This work suggests that the mobility increase with increasing source-drain voltage similar to the gate voltage dependent mobility phenomenon.

Keywords—p-channel; organic field-effect transistor; pentacene; mobility

I. INTRODUCTION

An inorganic field-effect transistor is widely used due to the advantages it offers to the electronic and information technology industries. In addition, the dramatic progress of electronic technology in the 20$^\text{th}$ century was made possible by high-performance silicon transistors known as metal-oxide-semiconductor field-effect transistor (MOSFETs) that revolutionized computer technology. Future efforts will then focus on the creation of more efficient and natural ways for human being interact with the complex information processed in these high-performance devices. However, during recent years, organic semiconductor material’s technology and application of them to transistor devices known as organic field-effect transistors (OFETs) has attracted scientific and technological interest. Organic semiconductor devices do not offer the same electrical performance as silicon devices. Thus, organic semiconductor technology appeals for lower-cost, cost-effective disposable electronics products while silicon technology is aimed for high-end, high-performance and high-processing power electronic products.

Although the conventional MOSFET has been a very popular research in the semiconductor field, OFET technology holds great promise to realize exciting new opportunities for broad-applications including large-scale coverage, inexpensive, light-weight and flexible electronics applications due to the organic semiconductor process ability advantages and unique physical such as electrical, optical, thermal and magnetic properties [1]. The interest for OFETs has extensively studied for broad applications such as flat panel active-matrix liquid displays (LCDs) or active matrix organic light-emitting diode displays (AMOLEDs), electronic paper (e-paper), low-end data storage or smart cards, radio frequency identification RFID) tags, low-cost disposable electronic products, and sensor arrays. Hence there will be more applications to evolve as the technology matures [2]. The organic semiconductor can be classified into two categories; polymers and small molecules, which exhibits semiconducting properties. These semiconductor exhibits great mechanical properties such as flexibility, toughness, and the ability to be processed such as roll-to-roll and ink-jet printing. In its simplest forms, an OFET comprises a conductive gate which could be the substrate covered by a thin dielectric films that is interfaced to the organic active semiconductor layer. MOSFET have higher field-effect mobility (600-250 cm$^2$/Vs for electron) than the organic based transistors. Low mobility leads to low frequency operation and this means that organic based electronics will be slower than silicon based circuits.

In this study, we demonstrate fabrication of bottom-gate/top source-drain contacts for small molecule (p-channel) pentacene-based OFET. The characterization of pentacene-based OFET was analyzed using MATLAB simulation.

II. DEVICE STRUCTURE, FABRICATION AND CHARACTERIZATION

A. Device structure and fabrication

Pentacene (p-channel) OFET with bottom-gate/top source-drain contacts configuration, in which the channel dimension of width and length are 2.5 mm and 50 μm, respectively was fabricated. The schematic structure of the pentacene-based OFETs is shown in Fig. 1. A Sb-doped n$^+$-type Si wafer was used as the substrate and gate contact to construct the transistor. A gate dielectric of SiO$_2$ layer with a 200-nm-thickness was thermally formed by dry oxidation. Pentacene (p-channel organic semiconductor) was then deposited by vacuum evaporation process to form a 50-nm-thick pentacene thin film onto the gate dielectric. Finally, a gold (Au) film of top source and drain contacts were
thermally vacuum evaporated through a designated shadow mask.

The current-voltage (I-V) measurements were performed in shielded box under atmospheric pressure at room temperature using a computer-controlled automatic electrical analyzer (Measure Jig MI-494), which is a source measure unit (SMU). The experimental setup is illustrated in Fig. 2. For electrical measurement, two probes which connected with Measure Jig MI-494 were carefully moved to the corresponding positions of source and drain contacts. The glove stage, which connected with external voltage source, was used to apply voltage to the bottom gate contact. For the output characteristic, the drain-source current ($I_{ds}$) was measured with the drain-source voltage ($V_{ds}$) was scanned according to setup voltage range. In every scan, the gate-source ($V_{gs}$) was held constant by an external voltage source unit while the $I_{ds}$ were recorded. Meanwhile for the transfer characteristic, the $V_{ds}$ was held constant, whereas the $V_{g}$ was scanned according to setup voltage range. The measurement and data recording was managed by MI-494 controller (ASAP System), which controls the automatic electrical analyzer instruments through GPIB ports.

**Figure 1.** Schematic cross-section structure of p-channel OFETs device. The width of the channel was 2.5 mm, its length was 50 μm, and the thickness of the SiO2 gate dielectric was 200 nm.

B. **Characterization using MATLAB simulation**

IEEE1620-2008 Standard for OFETs Characterization has been released and suggested that method for parameter extraction such as the mobility value, the threshold voltage, the on-off current ratio and the contact resistance, would be determined using classic theory of conventional MOSFET transistors [3]. A common model of field-effect transistors gives $I_{th}$ in the linear regime (at low $V_{ds}$) as:

$$I_{ds,lin} = \frac{W}{L} \mu C_i (V_{gs} - V_{th}) V_{ds}$$  \hspace{1cm} (1)

$I_{th}$ in the saturation regime (at high $V_{ds}$) is:

$$I_{ds,sat} = \frac{W}{2L} \mu C_i (V_{gs} - V_{th})^2$$  \hspace{1cm} (2)

W and L are the channel width and length, respectively. $\mu$ is the field-effect mobility, $C_i$ the geometric capacitance of the dielectric layer, $V_{gs}$ is the voltage applied to the gate contact, $V_{ds}$ is the voltage applied to the drain contact and $V_{th}$ is the threshold voltage. However, these two equations are valid under the assumption that the field along the channel is much lower than across it (gradual channel approximation) and the mobility is constant [4]. MATLAB simulation was used to extract parameters such as mobility from the electrical characterization of pentacene-based OFETs.

III. **RESULTS AND DISCUSSION**

A. **Output characteristics**

Figure 3 shows representative output characteristics, i.e., the drain-source current ($I_{ds}$) as a function of drain-source voltage ($V_{ds}$) for different gate-source voltage ($V_{gs}$) of pentacene-based OFETs on the highly doped n-type silicon substrate, respectively. The device shows a typical output curve of a field-effect transistor (FET) and undoubtedly indicates that only holes are accumulated at the semiconductor-dielectric interface and the current flow from the source to the drain through the channel region when negative gate voltages ($V_{gs}$) are applied. Therefore, the OFET is functioned in the p-channel operation in accumulation mode with increasing negative drain current ($V_{ds}$). The output characteristics can be distinguished in respect to the linear, the pinch-off and the saturation regimes which indicates a good ohmic contact pentacene and both source and drain electrodes.

**Figure 2.** Schematic diagram of experimental setup for electrical measurement.

**Figure 3.** Output characteristics of pentacene-based OFET. The output characteristics obtained from the experimental data where the $V_{gs}$ is set to five different constants.
B. Drain-Source voltage dependent mobility

The mobility, \( \mu \), which usually reported in units of \( \text{cm}^2/\text{Vs} \), is intrinsic property of the material and is an indicator of how readily charge is transported within the organic semiconductor upon application of an electric field. Thus, it can be calculated in the linear and saturation regimes using equation (1) and (2), respectively, as:

\[
\mu_{\text{lin}} = \frac{L}{WC_i} \frac{\partial I_{ds}}{\partial V_{gs}} \\
\mu_{\text{sat}} = \frac{2L}{WC_i} \left( \frac{\partial \sqrt{I_{ds}}}{\partial V_{gs}} \right)^2
\]  

(3)  

(4)

Concerning equation (1) and (2), the mobility is assumed to be a constant value in order to be used in analytical model. However, the mobility is depending on the gate-source and drain-source voltages which are not considered in the analytical model. Based on MATLAB simulation, the resulted mobility is summarized in Table 1. Table 1 represents results of MATLAB simulation depending on different constant \( V_{ds} \). In fact, from the results in Table 1, the extraction of mobility values from the experimental data is considered to be a voltage dependent quantity, which is derived from small signal measurements.

<table>
<thead>
<tr>
<th>Drain-source voltage, ( V_{ds} (V) )</th>
<th>Mobility (( \text{cm}^2/\text{Vs} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5</td>
<td>0.0234</td>
</tr>
<tr>
<td>-10</td>
<td>0.0262</td>
</tr>
<tr>
<td>-15</td>
<td>0.0261</td>
</tr>
<tr>
<td>-20</td>
<td>0.0258</td>
</tr>
<tr>
<td>Average</td>
<td>0.0254</td>
</tr>
</tbody>
</table>

Pentacene is a small-molecule p-type organic semiconductor which has confirmed high mobility upon proper deposition conditions [5]. The mobility can also be calculated in the saturation regime by finding the slope of the plot of square root \( I_{ds} \) vs. \( V_{gs} \) has obtained from equation (4). This technique provides the linear regime and the saturation regime for mobility value to be similar for a device, but this is not always the case [5]. The mobility extracted from plotting technique was 0.023 \( \text{cm}^2/\text{Vs} \) for the same device [6]. As is reported elsewhere [7], the mobility is gate voltage dependent, increasing with increasing \( V_{gs} \). Thus, this work indicates it also increase with increasing low source-drain voltage (\( V_{ds} \)). Moreover, the extracted mobility values suggested the analytical model should account for dependence of the OFET mobility upon the applied source-drain voltage or lateral electric field in organic semiconductor. Recently, the extended analytical model to describe the arbitrary electric field has been considered using Meyer-Neldel phenomenon with a Gaussien DOS distribution [8,9].

IV. CONCLUSIONS

In summary, we have fabricated the p-channel OFET using pentacene as an active semiconductor layer and silicon dioxide as gate dielectric layer in bottom-gate/top-source-drain structure. The device exhibited a typical output characteristic of a field-effect transistor (FET), which a conductive channel forms at the pentacene. The characteristics presented a well-defines the linear regime and saturation regime of device operation. Meanwhile, extraction of mobility parameter was obtained using MATLAB simulation based on classic theory of conventional MOSFET transistors. The mobility exhibited a linear dependence at low source-drain voltage. Thus, this suggested that source-drain voltage or lateral electric field needs to be considered in analytical model of OFET.

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