# Electrical and luminescence properties of MEH-PPV vertical organic light-emitting transistors with an ultra-thin aluminum source electrode

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Poly[2-methoxy-5-(2'-ethylhexyloxy)-p-phenylene vinylene] (MEH-PPV) based vertical organic light-emitting transistors (VOLETs) have been fabricated. The VOLETs were constructed with a bulk layer of indium-tin-oxide (ITO) and poly(2,3-dihydrothieno-1,4-dioxin)–poly(styrenesulfonate) (PEDOT:PSS) as a drain, organic electroluminescent layer of MEH-PPV, an ultra-thin aluminum (Al) as a source, lithium fluoride (LiF) as dielectric and a thick Al as a gate. Electrical and luminescence properties of the devices were investigated. In such VOLETs, the negative bias on the gate electrode has induced a high current density and brighter luminescence, which corresponding to a strong energy band bending in the MEH-PPV layer. Device physics of the fabricated VOLETs were discussed in detail.

## 1. Introduction

The first conjugated polymer has been reported by H. Shirakawa et al. [1] was a breakthrough in polymer science field. Since then, interest in the conjugated polymer research was rapidly expanded to a wide category including conducting, semiconducting, and smart materials. Among of them, the polymeric semiconductor has been intensively developed and researched due to their functionality and variety in the application, such as good conductivity in organic field effect transistors (OFETs), high purity of color in organic light-emitting diodes (OLEDs) and environmental friendly materials in organic photovoltaics (OPVs) [2]. Poly(p-phenylenevinylene) (PPV) has shown a great potential as a multifunction semiconducting polymer material since it can be utilized in OFET [3,4], OLEDs [5–8] and OPVs [9,10], depending on its derivatives. One of its derivative named MEH-PPV has been used in OLEDs research due to its ability to emit a pure orange light output [5]. High solubility in common organic solvent and high glass transition temperature makes it easier to be deposited in such device by solution processing technique [11,12].

In parallel with a vast development of the semiconducting polymer, organic electronic technology has been rapidly evolved to be more efficient, multifunctional, compact in size, flexible in shape and reliable for consumer application. Vertical organic light-emitting transistors (VOLETs) has been a great example of multifunctional devices where they can produce a light emission and modulate a current at the same time [13]. An integration of OLEDs and OFETs in this device does not only simplify the fabrication process and cut down the production cost but also can overcome a challenge of backlight issue of flat panel display in future. In actual architecture, VOLETs were fabricated by combining capacitor cell and OLEDs, interconnected with a source electrode in between them. In the capacitor cell, dielectric or insulator layer was used to accumulate charge driven by a gate voltage. The accumulated charges were then modulating carrier injection at source/polymer interfacial layer. The injected carriers where then transported and recombined to release an emission in the semiconductor layer of OLEDs.

Nonetheless, VOLETs based on small molecules as the organic semiconducting materials were commonly been reported, instead of the polymer [13–15]. In order to show a potential of MEH-PPV in both OLEDs and OFETs, A.H. Reshak et al. has reported an electrical behavior of MEH-PPV based VOLETs [16]. However, the paper only focuses on the electrical properties of VOLET with different thickness of MEH-PPV. No result on electroluminescence was presented and the device physics on the current modulation by gate voltage was not clearly explained.

Previously, we have reported on fabrication and characterization of small molecules Tris(8-hydroxyquinolinato) aluminum (Alq$_3$) based VOLETs [17]. In this paper, we demonstrated electroluminescence properties of MEH-PPV based VOLETs. Current and luminance of the VOLETs were analyzed in terms of output and transfer characteristics. Physical mechanisms such as injection, transportation, and recombination of charged carries were discussed in detail.

## 2. Experimental

Pre-patterned ITO (Ossila Ltd.) coated glass substrate was ultrasonically cleaned in DeconTM solution and subsequently rinsed with deionized water, acetone, and isopropanol before dried with nitrogen gas purge. A hole injection material of PEDOT:PSS (Heraeus Clevios GmbH) was spin-coated onto the cleaned ITO substrate at 2500 rpm for 40 s, and baked at 120 $^o$C for 30 minutes to removes residual water. For emissive layer, 4 mg/mL of MEH-PPV from chlorobenzene solution was spin-coated at 800 rpm onto the PEDOT:PSS layer to obtain ~47 nm thick film and baked on a hot plate at 100 $^o$C for 30 mins. A 20 nm thick of Al source electrode was thermally evaporated followed by 150 nm LiF as a dielectric layer. Finally, 100 nm thick of Al was thermally evaporated as the top gate electrode. The VOLET construction was presented in Fig. 1. The VOLETs were fabricated in the glove-box with nitrogen environment and encapsulated before tested to avoid degradation and ensure the results stability.

The thickness of the thin films was measured using a profilometer (Tencor, P-6). Current-voltage-luminance (J-V-L) properties of the VOLETs were characterized using chroma meter (Konica Minolta, CS-200) connected to a dual channel source measure unit (Keithley, 2600). All measurement were performed at room temperature. The device fabrication and characterization were repeated 6 times ensure the repeatability.
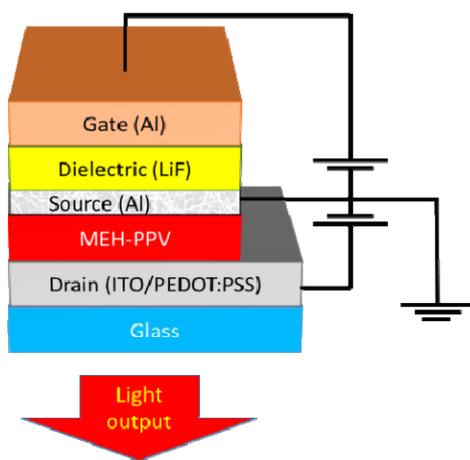


Fig. 1. Device architecture of VOLETs fabricated
in this work

## 3. Results and discussion

Fig. 2 shows output current and luminance characteristics of the fabricated VOLETs. Potential different between source and drain ($V_{DS}$) was swept from 0 to 10 V for all sample. Gate to source voltage ($V_{GS}$) was varied from +3 V to -1 V for each $V_{DS}$ swept. The current density of $V_{DS}$ was increased by increased in negative value of $V_{GS}$. Turn-on voltage for the VOLETs observed

reduces towards lower voltage when the $V_{GS}$ more negative $V_{GS}$ was applied. A similar trend was observed for the luminance graph as shown in Fig. 2 (b) where the light intensity increases by the increment of negative value of $V_{GS}$. This modulation behavior of current density and luminance are known as transistor effects since the $V_{GS}$ was used to control the intensity and characteristic of both parameters.

The important key to this modulation behavior is the special porous features of the aluminum source electrode. Fig. 3 shows the SEM image of the 20 nm thin aluminum electrode. From the SEM image, several holes were observed within the size of 500 to 900 nm in diameter. These holes are relatively bigger than the thickness of the aluminum. The large size of the hole as compared to the thickness of the aluminum resulting discontinued porous structure [13]. The function of these holes and the ultra-thin layer of aluminum is to allow energy band contact between emissive materials and the gate electrode. Upon an appropriate $V_{GS}$, the energy band of the emissive materials can be tuned and spontaneously modulate the current density as well as the luminance intensity.



(a)



(b)
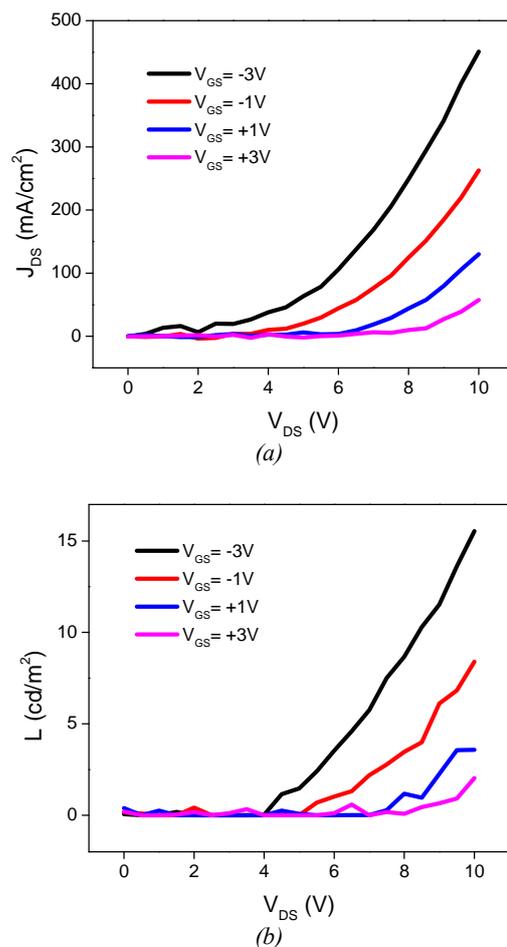
Fig. 2. Output (a) current and (b) luminance
of VOLETs
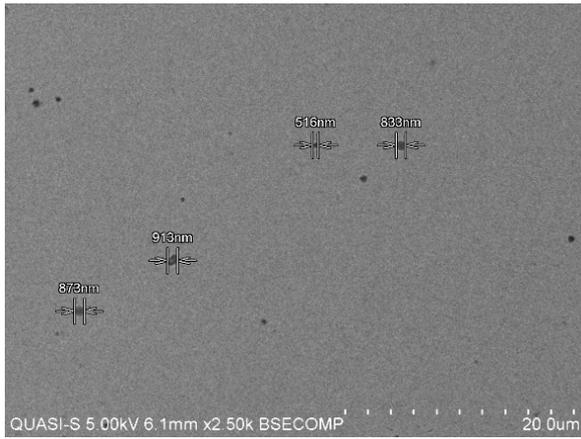
*Fig. 3. SEM image of 20 nm aluminum source electrode.*
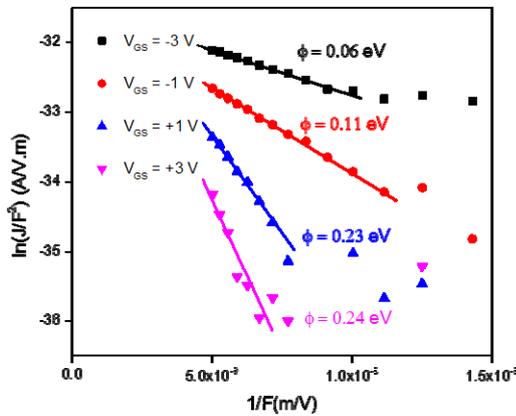


*Fig. 4. FN plot of VOLETs at the different gate voltage.*

VOLETs. At $V_{GS}=0$, the VOLETs is acted as the ordinary OLEDs. Under significant voltage across drain and source, the current will exponentially increase after entering the space-charge limited-current (SCLC) region and light will start to emit and become brighter for higher $V_{DS}$. At the $V_{GS} > 0$, the positive charge will be accumulated at the MEH-PPV/Al interface and increased the potential barrier height, which results in a reduction of an injection process of the electron from the source into MEH-PPV layer. The other situation is when the $V_{GS} < 0$, since the gate was biased with the negative potential, the electron will be accumulated at the MEH-PPV/Al interface and lowering the potential barrier height, which significantly improved the injection of the electron into the emissive MEH-PPV layer. The light emission intensity is directly proportional to the amount of charged carrier accumulated in the MEH-PPV layer. High exciton formation from the high population of charged carrier accumulation will produce the high intensity of light.

In order to understand physics behind the current and luminance modulation of the VOLETs, an injection property at the MEH-PPV/Al interface was evaluated by applying the Fowler-Nordheim (FN) theory. The FN model can be described mathematically by $J=AF^2exp(-K/F)$, where $J$ is current density, $A=q^3/8\pi h\phi$ and $K=8\pi(2m^*)^{1/2}\phi^{3/2}/3qh$, here $\phi$, $m^*$, $q$, and $h$ are potential barrier height, the effective mass of charge carrier, elementary charge, and Planck constant, respectively. The FN theory ignores dependency of temperature and has been used to explain the injection mechanism of metal/organic semiconductor interface [18,19]. From the theory, potential barrier height at the MEH-PPV/Al interface was calculated based on the output current characteristic of the device. Fig. 4 shows the FN plot of the VOLETs at different $V_{GS}$ value. It was found that the potential barrier height at the MEH-PPV/Al interface was reduced significantly when the $V_{GS}$ was biased towards higher negative magnitude. This result indicates that the modulation of the output current and luminance were directly related to the reduction of the potential barrier height at the MEH-PPV/Al interface.

Fig. 5 shows the schematic diagram of injection mechanism of the electron at MEH-PPV/Al interface at a different condition of $V_{GS}$. These schematic diagrams are presented to illustrate the charged carrier behavior in the



*Fig. 5. Schematic diagram of energy band alignment at MEH-PPV/source/dielectric/gate of VOLETs at the different gate voltage*

*(a)*



*(b)*
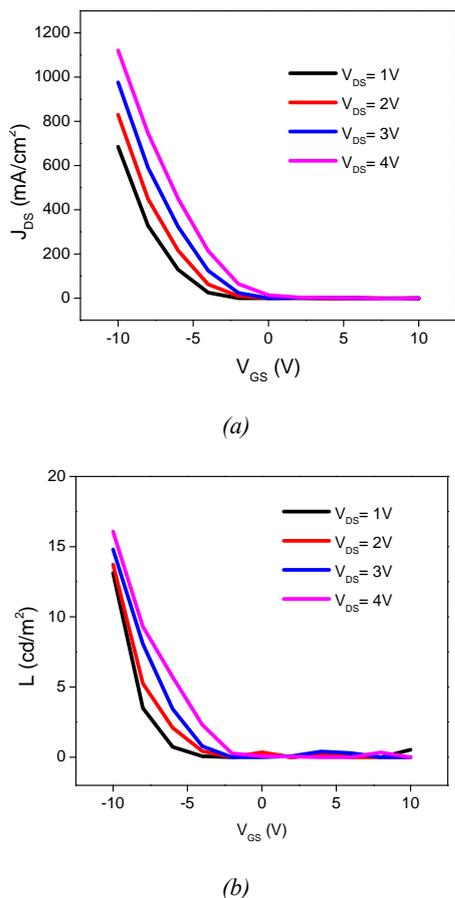
Fig. 6. Transfer characteristics of the VOLETs.

Another important parameter of the VOLETs is a transfer characteristic. Fig. 6 show the transfer current and luminance characteristic of the VOLETs. The transfer characteristics were taken from -10 to 10 V of $V_{GS}$ with the different bias of $V_{DS}$. The current and luminance intensities were dropped when the $V_{GS}$ was swept from -10 to 0 before they remained at the lowest values within the positive range of $V_{GS}$. The current and luminance intensity also increases when the $V_{DS}$ in increased from 1 to 4 V. This results show that the negative $V_{GS}$ is referred as on-state and the positive $V_{GS}$ is referred as off-state of the VOLETs.
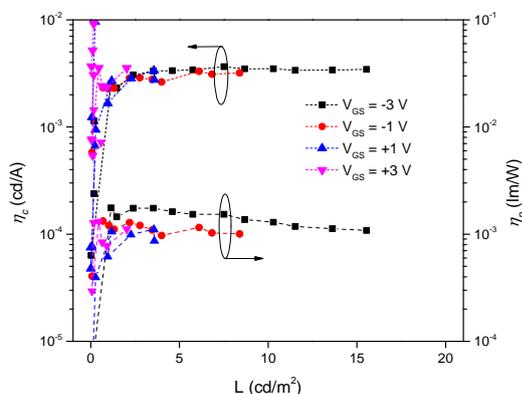


Fig. 7. Efficiencies of VOLETs at different gate voltage.

The efficiencies of the VOLETs is divided into 2 types, current and power efficiencies, which were adopted from OLED analysis and considering the output characteristics as a basic calculation. Fig. 7 shows the current and power efficiencies of the VOLETs at different $V_{GS}$. It is found that the efficiency of the VOLETs is increasing when the $V_{GS}$ biased at higher negative value. It is postulated that the amount of exciton radiative recombination is higher when the $V_{GS}$ was biased with the negative voltage, which finally results in brighter luminance with relatively low current density. It is also suggested that the improvement of the electron injection by negative $V_{GS}$ facilitate more balance of hole-electron accumulation in the emissive layer since the nature of MEH-PPV is known as p-type materials which hole carrier mobility is dominated.

## 4. Conclusions

The EL properties of MEH-PPV based VOLETs have been demonstrated. The current and luminance properties of the VOLETs have been analyzed in terms of output and transfer characteristics. The porous structure is an important feature for source electrode in VOLETs fabrication. The fabricated VOLETs can be modulated with a minimum $V_{GS}$ of 1 V. Modulation of current by $V_{GS}$ in the VOLETs was related to the change in magnitude of potential barrier height at the MEH-PPV/Al interface. Efficiencies of the VOLETs were higher at stronger negative $V_{GS}$ due to more balance in exciton formation and recombination.

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