Fabrication and Characterization of Solution Processed Top-Gate-Type Organic Light-Emitting Transistor


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Tris(8-hydroxyquinolinato) aluminium (Alq₃) based top-gate-type organic light emitting-transistors (OLETs) have been fabricated by using a simple solution process. The OLET consists of a bulk layer of indium-tin oxide (ITO) and hole injection layer of poly(2,3-dihydrothieno-1,4-dioxin)–poly(styrenesulfonate) (PEDOT:PSS) as an anode (source), organic electroluminescent layer of Alq₃ and aluminium (Al) as cathode (drain) and gate. A Current–voltage–luminance (J–V–L) characteristic of the OLETs shows that the current density is depended on polarity of gate bias. Initial internal electric field contributes to the charge diffusion between gate and cathode channel. A vice versa characteristic observed for luminance at cathode–anode and gate–anode channels.

Keywords: Organic Light-Emitting Transistor, Alq₃, Spin-Coating, Electroluminescence.

1. INTRODUCTION

Since the discovery of organic field-effect transistors (OFETs)¹ and efficient organic light-emitting diodes (OLEDs),² organic semiconductors have become a promising material for the production of planar solid state lightning and displays. Unlike inorganic field-effect transistors (FETs), the charge carrier transportation in OFETs behaves as an unipolar n-type, p-type or even ambipolar.³ In ambipolar OFETs, the electrons and holes are possible to be transported in the same device depending on the applied voltage and types of organic semiconducting material used. For specific organic semiconducting materials, the recombination of electron and hole in such an ambipolar OFETs can result in the generation of emission spectra depending on their band gap.⁴,⁵ This concept is also applied for the light emission of the OLED devices. The OFETs device that can produce light is known as organic light-emitting transistor (OLETs). The OLETs device that can produce light is known as organic light-emitting transistor (OLETs). OLETs are multifunctional organic devices that combine the current modulation function of a transistor with the light emission.

Several designs of OLETs have been reported to date. Kudo et al. has utilized a combination of combining static induction transistor (SIT)⁶ with organic light emitting diode to fabricate the OLET and investigate the static and dynamic characteristics of the device.⁷ Multilayer SIT type of OLET has been reported by Lee et al.⁸ Recently, it has been reported that the lithium fluoride (LiF) layer was deposited in between the gate and source electrodes of MEH-PPV based OLET.⁹ Other groups fabricate the OLET with dielectric or insulator layer to form a depletion region in order to control the amount of charge carrier by varying the gate voltage.¹⁰–¹⁴ This kind of structure is known as organic light-emitting field effect transistors (OLEFETs).

In 2004, Park et al.¹⁵ have reported the electroluminescence (EL) characteristic of a top-gate-type OLET. The OLET is consisted of patterned indium thin oxide (ITO) as drain and source planar electrodes, followed by organic transporting and emissive layers and top aluminium (Al) electrode which acts as a gate. The fabrication process is similar to the normal single-layer OLED fabrication,¹⁶ except the ITO was patterned to form drain and source electrode, separated with a gap size of 30 μm. The device was prepared in a glove-box, and the organic layers are deposited using a thermal evaporation method.

In this paper, the OLET has been fabricated by patterning the Al metal layer to form cathode and gate electrodes with a gap of 50 μm. Simple solution process has been employed to form the emissive layer. The device was prepared outside the glove-box. Current and EL characteristics, and light switching for both cathode and gate channels were investigated with respect to the gate biases.
2. EXPERIMENTAL DETAILS

Figure 1 shows the molecular structure of Alq₃. The Alq₃ used in this experiment was purchased from Sigma Aldrich. The Alq₃ solution at concentration of 15 mg/ml was prepared by dissolving 30 mg of the Alq₃ powder into 2 ml chloroform solvent. The solution was stirred for 1 hour to ensure it was completely dissolved. ITO substrates were patterned by covering a part of the surface with Kapton® tape and etching with diluted hydrochloric acid (HCl:deionized, 1:1) at temperature of 100 °C. The ITO substrates were then ultrasonically cleaned in Decon™ aqueous for 15 minutes, followed subsequently by deionized water, aceton and isopropanol. PEDOT:PSS solution was then spun coated on top of the cleaned patterned ITO substrates at the spin rate of 7000 rpm for 20 s. The Alq₃ solution was then spun coated on the PEDOT:PSS layer at the spin rate of 1500 rpm for 40 s. The devices were soft-baked using a hot plate at 100 °C temperature for 60 s after each of spin-coating steps to remove the remaining solvent. Measured thickness of the PEDOT:PSS and the Alq₃ layers was 20 and 63 nm, respectively. Finally, a top electrode of Al metal was evaporated through a special mask in vacuum condition of $2 \times 10^{-5}$ mbar. A 50 μm diameter of copper wire has been use to form a gap between cathode and the gate. Figure 2. shows a schematic diagram of the evaporation process.

Current–voltage–luminance ($J$–$V$–$L$) characteristics of the OLET devices were performed by using a Konica Minolta CS-200 chroma meter. The cathode electrode was grounded while the gate electrode was negatively and positively biased. The voltage was swept from 0 to 20 V between cathode and anode for each gate bias. Measurement was performed in room temperature, and the fabricated device is not encapsulated.

3. RESULTS

Figure 3 shows $J$–$V$ curve of the OLET device for gate biased from +5 to −15 V. Current density is increases when the gate sweeps from positive to negative bias. The knee voltage ($V_o$) of the device is reduced from 15 to 13.5 V for gate biased from +5 to −5 V, respectively. Rapid increase in the current density can be observed when the magnitude of negative bias is increased up to −15 V. Consequently, the $V_o$ of the device shows a great reduction of 6.5 V when the bias gate is set to be −15 V.

Figure 4 shows the luminance–voltage ($L$–$V$) characteristic of the device. A unique $L$–$V$ characteristic can be observed where the luminance trend from cathode–anode (CA) channel is vice versa compared to the gate–anode (GA) channel. The luminance intensity pattern of the CA channel was observed to reduce when the gate bias turned.
from +5 to −5 V. The turn on voltage ($V_{on}$, when $L = 1 \text{ cd/m}^2$) of the device was increased from 18 to 19.5 V. On the other side, the light output intensity of the GA channel was observed to reduce rapidly until no emission has been detected (for $L = 1 \text{ cd/m}^2$ when the gate electrode was set to be 0 and 5 V. The $V_{on}$ at this channel is 18 V for −5 V gate bias.

4. DISCUSSION

Figure 5 shows a schematic diagram of the EL mechanism of the OLETs for both, positive and negative bias on the gate. When the gate was positively biased, holes are injected from anode and transported into the Alq$_3$ layer. However, the holes are not injected from the gate due to the large barrier high (between LUMO level of the Alq$_3$ and work-function level of the aluminum gate electrode (see Fig. 6)). The injected electrons was then traveled and attracted into CA channel as the applied bias for this channel was increased. At the same time, holes and electrons are injected from cathode and anode, respectively. Accumulation of the exciton in CA channel becomes high as the increasing of $V_{CA}$ followed by a recombination process which leads to a high EL emission. No recombination occurred at GA channel because no electron enters this path to recombine with holes from the anode.

When the gate was negatively biased, electron and hole are injected from gate and anode, respectively, into the GA channel. An initial electric field has been created in the GA channel. When the $V_{CA}$ bias is increased, electrons was injected from cathode and divert into the GA channel due to the initial field. Thus, more recombination of exciton was occurred at GA channel as compared to the CA.
Fabrication and Characterization of Solution Processed Top-Gate-Type Organic Light-Emitting Transistor

Sarjidan et al.

Fig. 6. Energy band diagram of OLET.

channel. A significant increase in luminescence intensity and reduction of $V_{on}$ can be observed in Figure 7.

It is noted that the Alq$_3$, also known as an electron transporting materials. The mobility of the electrons is higher than the hole. However, from the energy diagram of the device, the holes are easier to be injected into the Alq$_3$ as compared to the electrons because the barrier height of the hole is lower compared to the barrier height of electron. Assuming that the density of the holes injected from the anode is similar for both GA and CA channels, negative biased gate resulted in more electrons injected into the Alq$_3$ layer. The density of electron in the GA channel was higher compared to in the CA channel because the electron from the CA channel is attracted to the GA channel due to the initial electric field. Thus, more recombination of an electron–hole pair occurs at the GA channel resulting in high luminance compared to the CA channel. This can be observed by plotting the ratio of $L_{GA}/L_{CA}$ (see Fig. 8). The ratio obtained increases when more negative bias was applied at the gate.

Current density, $J$, of the device increases rapidly with an increase in magnitude of negative bias at the gate electrode. As mentioned earlier, electron is a dominant charge carrier of the Alq$_3$ molecule. Thus, the electron transportation is the major contribution for the current density reading. More electrons will be injected into the Alq$_3$ layer when the gate is negatively biased. However, a slight reduction in current density is observed when the gate is positively biased due to more holes being injected compared to electron into the Alq$_3$ layer.

5. CONCLUSIONS

Alq$_3$ OLET has been fabricated using solution processed, and the EL properties of the device have been characterized. The current characteristic of the device is depending on electron transportation in emissive layer. The initial internal electric field plays an important role to attract the electron flow into the respective channel. The luminescence characteristic shows a vice versa pattern between gate and cathode channels. The ratio of light intensity also depends on exciton accumulation as a respond to the gate bias.

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References and Notes


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