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Thermal analysis of active layer in organic thin-film transistors

Moo Whan Shin [a,*], Sun Ho Jang [b]

[a] School of Integrated Technology and YICT College of Engineering, Yonsei University, 162-1 Songdo-dong, Yeonsu-gu, Incheon 406-840, Republic of Korea
[b] Department of Materials Science & Engineering, Myong Ji University, 38-2 Nam-Dong, Yongin, Kyunggi 449-728, Republic of Korea

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ABSTRACT

This paper reports on the direct thermal observation of the pentacene – based organic thin-film transistors (OTFTs) under the real operating conditions. Liquid crystal (LC) spreading method was utilized for the thermal investigation of an active layer of the OTFT package. Temperature variation in the OTFT package was recorded for the different input power and significant heat generation was observed in the confined active layer. Detailed thermal performance of the OTFT package was projected using a Computational Fluid Dynamics (CFD) method as well. It was shown that the driving of the OTFT package with the drain voltage of −15 V resulted in the active layer temperature of about 53.2 °C. The result indicates that the device design with effective thermal dissipation is imperative for reliable operation of the OTFT package.

1. Introduction

For several years, organic thin film transistors have been the subject of intensive investigation. The mobility values of some the OTFT reached at the level suitable for the low speed electronic applications that require an electrical performance similar to that of amorphous silicon TFT [1,2]. Pentacene-based OTFT have made progress toward low-cost electronics and switching element for flat-panel displays [3], because the characteristics of such devices are approaching or even surpassing those of amorphous silicon devices [4]. However, inherently strong thermal sensitivity of organics is known to be one barrier that must be overcome for the commercial realization. In the OTFT package, the temperature rise can significantly affect the electrical performance and lead to delamination of the OTFT package. Mobility is the key device parameter affecting electrical performance in the OTFT package. The mobility of pentacene is reported to change with temperature. In general, the mobility is increased with temperature until a peak temperature is reached and starts to decrease above the peak temperature. The peak temperature in pentacene is known to vary depending on different device structures and processing conditions. A peak temperature about 50 °C was reported [5], but many report peak temperatures in a temperature range lower than room temperature [6–8]. Therefore, it is highly desirable to effectively dissipate self heating from the active layer of OTFT. In addition, delamination is possibly induced at high temperature in organic materials and is directly responsible for mechanical reliability problems [9]. Despite of the importance of the thermal information of the active layer in the OTFT package, there have not been found any reports on the subject so far to the best knowledge of the authors.

In this report, thermal characterization of OTFT package is demonstrated using the LC spreading method and the CFD solver. Liquid crystal spreading method [10,11] was employed for the visualization of hot spot in the OTFT package and Computational Fluid Dynamics (CFD) method was utilized for the determination of the temperature in the active layer.

2. Experimental method

The organic thin film transistor (OTFT) investigated in this study was fabricated in the inverted coplanar structure as is shown in Fig. 1. The characterized OTFT package is

* Corresponding author.
E-mail address: mwshin@yonsei.ac.kr (M.W. Shin).

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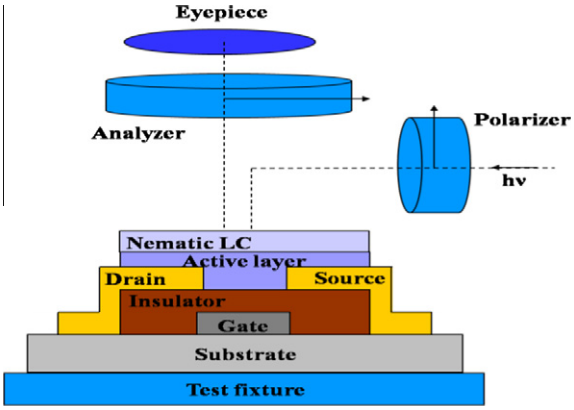

Fig. 1. Schematic of the experimental set-up for the surface temperature measurement of the OTFT package.

Table 1
Thermal parameters of materials in the OTFT package.

Materials	Thermal conductivity (W/mK)
SiO_2 (insulator)	1.38
Pentacene (active layer)	1.85
Si (substrate)	130
WSi (gate layer)	174
Au (electrodes)	317

composed of an active layer of pentacene with a thickness of 100 nm, a width of 20 μm, a length of 2 μm, an insulator of SiO_2 with a thickness of 300 nm, WSi gate layer with a thickness of 150 nm, and Si substrate.

Fig. 1 shows the schematic experimental set-up of thermal measurement with the cross section of the investigated OTFT sample. A linear polarizer is placed in front of the illumination source of the microscope to make the sensing light linearly polarized. The linear polarizer further increases the extinction ratio of the polarization. The polarization of the sensing light is critical in obtaining clear thermal images with high contrast. The transient temperatures of order–disorder in LC depend on the ratio of composition and materials. The liquid crystal for our research is composed of octyloxy cyanobiphenyl (8OCB) and octyl cyanobiphenyl (8CB) with a transient temperature of 54 °C.

Based on the structure of the fabricated OTFT package, numerical thermal analysis of the OTFT package was performed using the Finite Volume Method (FVM) in Computational Fluid Dynamics (CFD) solver (Flotherm V8.1, Mentor Graphics Ltd.) [12]. The CFD method carries out a full 3D solution of the Navier–Stokes equations for mass, momentum and energy conservation using the finite volume technique. The equations are transformed into an algebraic form that can be solved numerically. These equations are solved by an iterative process for a given set of boundary conditions. Table 1 displays several components of the OTFT package with their thermal conductivities for simulation.

3. Results and discussion

The electrical output characteristics of the OTFT package at a natural cooling condition have been measured as a function of the drain voltage at constant gate voltage. Under the natural cooling condition, it is assumed that there is no external forced conduction and convection. The condition is achieved by measuring the package in the still air chamber described by (JEDEC 51–2) [13]. The electrical measurement of OTFT package shows the common emitter characteristics of a typical OTFT package. The gate voltage V_G was decreased from 0 to −10 V in a step of −5 V.

At low drain voltage, V_D, the drain current increases proportionally to the drain voltage. The well-defined linear and saturation regions are observed with a saturation current around -4.0×10^{-6} A under the gate voltage of −10 V.

Based on the output characteristics of the OTFT package, the thermal characteristics of the OTFT package were investigated using the LC spreading method and the CFD solver. By analyzing the surface temperature using LC spreading method, the surface temperature of OTFT package was found to increase with the driving input power.

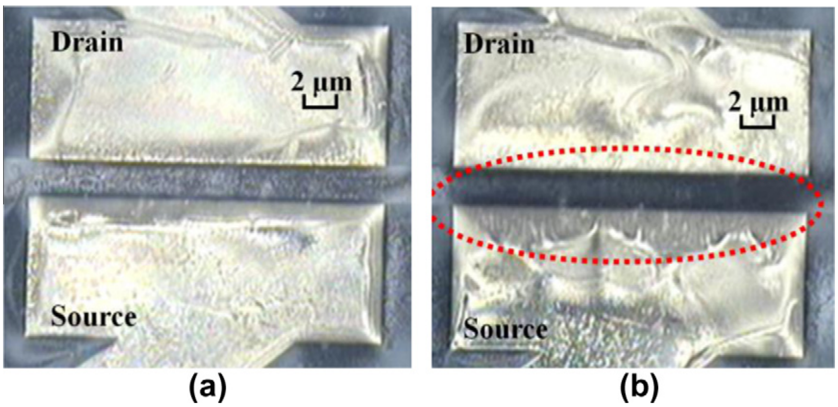

Fig. 2. The hot spot (red oval parts) on the OTFT package as a function of drain voltage (*VD*), using LC spreading method. (a) −5 V and (b) −15 V (gate voltage = −10 V, natural cooling condition). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The temperature of active layer was observed to exceed transient temperature (54 °C) of liquid crystal. Fig. 2 clearly shows that the behavior of hot spot on the OTFT package was changed when the driving power is increased from in −5 to −15 V. The area of hot spot indicated in the oval dotted line has been concentrated in the active layer and expanded to other side of package surface with increasing the driving power. This means that the surface area with a temperature of 54 °C, or higher, is expanding by the heat generation from the operation of OTFT package. The thermal characteristics of the OTFT observed by the LC spreading method were compared with thermal simulation by the CFD method for better quantitative analysis.

Fig. 3(a) is the simulated temperature contour of OTFT with V_D of −15 V and V_G of −10 V. The temperature of active layer was calculated to be about 53.2 °C and is in a good agreement with the experimental results from the LC spreading method. It is worth while noting that the heat flow from the active layer region is very poor in both vertical and planar direction due to very low thermal conductivities of both active layer (with a thermal conductivity of 1.85 W/mK) and insulator layer (with a thermal conductivity of 1.38 W/mK). In particular, low thermal conductivity of insulator layer leads to very poor thermal characteristics for the OTFT with an inverted coplanar structure as is the sample investigated in this study. The variation of temperature of an active layer as a function of drain voltage was presented in Fig. 3(b). The active layer temperature of the OTFT package was shown to be very sensitive to the drain voltage. The temperature was shown to increase from 26.68 °C at the drain voltage of −5 V to 53.2 °C at the drain voltage of −15 V. With increasing of temperature in the active layer, the mobility was found to decrease. The variation of mobility with the drain voltage was calculated using the Eq. (1) below and was also presented in Fig. 3(b).

$$I_D = \frac{WC_{ox}}{L}\mu\left(V_G - V_T - \frac{V_D}{2}\right)V_D, \qquad (1)$$

where I_D is the drain current, W the width of active layer, L the length of active layer, C_{OX} the capacitance, V_G the gate voltage, and V_T the threshold voltage. The results imply

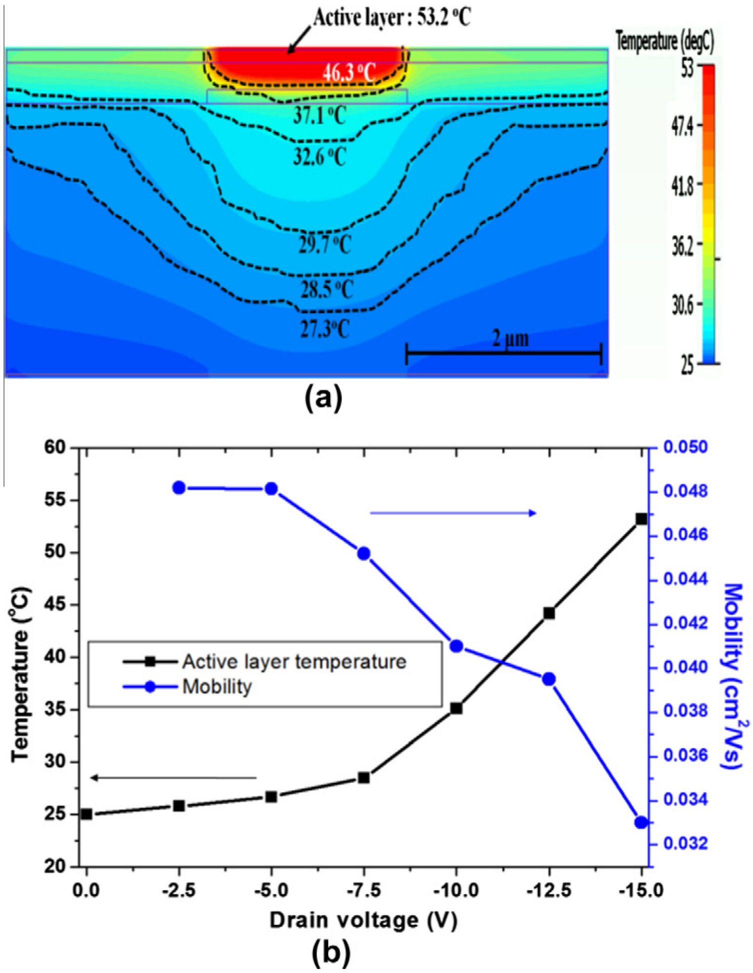

Fig. 3. (a) The thermal distributions (cross section) of the OTFT packages under a natural cooling condition (drain voltage is −15 V). (b) Variation of the temperature and mobility with the drain voltage in the active layer of OTFT package (gate voltage = −10 V, natural cooling condition).

that the thermal design of OTFT package directly affect its electrical performance and thus effective heat dissipation is critically important for reliable operation.

4. Conclusions

In this paper, thermal characterization of OTFT package was demonstrated using the LC spreading method and the CFD solver. The hot spot of the OTFT package was generated and was expanded with input power in the LC spreading method. The temperature change in the active layer of the OTFT was calculated using the CFD solver for different input powers. The results from the thermal measurement and simulation were in a good agreement each other. It was found that the temperature of active layer of OTFT was very sensitive to the input power and exhibited very poor thermal dissipation due to very low thermal conductivity of the active layer and insulator layer. The mobility of OTFT was decreased with the drain voltage. The results indicate that the device design for effective thermal dissipation is imperative for reliable operation of the OTFT package. A novel thermal evaluation method for the OTFT package was established.

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