Influence of Substrate Thermal Conductivity on OLED Lifetime

Seungjun Chung[1], Jae-Hyun Lee[2], Jaewook Jeong[1], Jang-Joo Kim[2] and Yongtaek Hong[1]
[1]Dept. of EECS, Seoul National University, Seoul 151-744, KOREA
TEL:82-2-880-9567, e-mail: yongtaek@snu.ac.kr.
[2]Dept. of MSE, Seoul National University, Seoul 151-744, KOREA.

Keywords : OLED, thermal conductivity, thermal stress, lifetime, degradation

Abstract

Temperature increase during OLED operation can significantly degrade the device lifetime. By using top-emission OLEDs fabricated on glass and silicon substrates that have different thermal conductivities, we found that efficient heat dissipation and corresponding lifetime improvement can be obtained by making a direct contact between the OLED anode and the high thermally-conductive silicon substrate. We describe substrate-dependent OLED heat dissipation behavior and OLED lifetime improvement by using infrared camera images and constant current stress test methods.

1. Introduction

Organic light-emitting diode (OLED) is one of the most promising candidates for the next generation flat panel display technologies mainly because of low driving voltage, high brightness, high efficiency, wide viewing angle, and conformability on flexible substrates [1-3]. Although OLED technology is now much matured, it is still necessary to further investigate its degradation mechanisms for device reliability improvement. One of the main factors in OLED degradation is morphological change induced by the thermal degradation from the elongated electrical stress [4]. Input electrical power of an OLED is closely related to the temperature increase with operation time because most of the input electrical power of the OLED is typically considered to be converted into thermal energy in the device [1]. The OLED temperature can go up to 80°C for conventional display or lighting operation conditions [2]. As the device temperature increases, organic layers, especially hole transport layer (HTL), can be crystallized, causing catastrophic failure or thermal breakdown in OLEDs [5-7]. In addition, thermal stress can change surface properties of the organic layers [2] and eventually accelerate degradation process of the organic materials, resulting in OLED lifetime reduction and luminance non-uniformity [1]. Although it is well known that the temperature increase of the OLEDs can degrade the device performance and lifetime, few researches have been performed to investigate heat localization due to poor thermal conductivity of the substrates. Therefore, it is important to analyze the relationship between the input electrical power and temperature increase in OLEDs, focusing on heat dissipation of the OLEDs and corresponding lifetime improvement. In addition, reducing the thermal stress of OLEDs without any additionally installed cooling equipment would help improving OLED lifetime. In this paper, we report substrate-dependent heat dissipation of a top-emission OLED when its reflective anode is directly contact with the substrate (silicon and glass). It was found that efficient heat dissipation through the highly thermally-conductive silicon substrate can significantly improve the OLED lifetime.

2. Experimental

We fabricated top-emission OLEDs on glass (0.5 mm thick) substrates and silicon wafer (0.55 mm thick) coated with a thermally grown oxide layer (200 nm). Since the oxide layer is very thin in comparison with the silicon wafer, we believe that the silicon would play a major role for thermal dissipation. Thermal conductivities of the silicon and glass are 150 and 1W/m·K, respectively. The fabricated OLEDs have the following structure: silver anode (300 nm) / molybdenum oxide ($MoO3$) as hole injection layer (HIL) (4 nm) / a-napthylphenyl biphenyl diamine (NPB) as HTL (54 nm) / tris-(8-hydroxyquinoline) aluminum (Alq3) as electron transport and light emissive layer (ETL/LEL) (53 nm), ytterbium (1 nm) / silver (20 nm) semitransparent cathode, and Alq3 index-matching layer (45 nm). All layers were sequentially deposited without breaking vacuum.

Finally, fabricated devices were encapsulated with glass caps with desiccant in them. Lifetime was measured by using Polaronix M6000T from McScience. Several levels of constant current were applied to OLEDs and voltage increase and luminance reduction were monitored in situ. Since the OLED lifetime can be also closely related to the surface roughness of the substrates and the reflective anodes, we measured the surface roughness of the silver anode on both glass and silicon substrates using atomic force microscope (AFM) equipment from Park System.

An infrared (IR) thermal image camera from FLIR systems (A60M) was used to accurately measure heat distribution over the substrate at different luminance levels of 2000, 5000 and 10000 cd/m^2. We measured changes in the heat distribution images and corresponding peak temperature increase from the backside of the substrates as the OLED operation time increases.

3. Results and discussion

Figure 1(a) shows current density and luminance versus voltage characteristics for OLED fabricated on silicon and glass substrates. Luminance versus current density is also included in Fig. 1(a). Figure 1(b) shows luminous and power efficiencies versus current density characteristics for both devices. As shown in the figures, performances of the fabricated OLEDs were verisimilar. Luminous and power efficiencies of OLEDs on silicon and glass substrates were 9.34 and 9.03 cd/A and 3.54 and 3.70 lm/W at 10000 cd/m^2, respectively.

Figure 2 shows IR camera images presenting heat distribution through the silicon and glass substrates when the OLEDs operated at luminance of 2000, 5000 and 10000 cd/m^2. The images also show progression of the heat distribution with time. The temperatures under each image represent the peak temperature in each thermal image. As shown in the figure, peak temperature of the silicon substrates became saturated earlier than that of the glass substrates because the high thermal conductivity of the silicon substrates efficiently dissipate the heat generated inside the OLED and the substrate temperature became relatively fast saturated. Even at luminance of 10000 cd/m^2, the silicon substrate showed little heat distribution over the substrate and the resulting peak temperature was increased by only 1.2 °C. On the other hand, for the OLEDs on glass substrates, heat distribution is highly localized around the OLED light-emitting area (3×3 mm^2) because of the poor thermal conductivity of the glass substrates. At 10000 cd/m^2, peak temperature was increased as high as 64.5 °C, which is similar to organic material glass transition temperature (Tg). At this temperature, the organic layers are known to be crystallized and accelerate the degradation processes.

Although heat generated from the OLED will be typically radiated to all directions, most of the generated heat is expected to be dissipated through the substrate into air because thermal conductivity of the metallic anode and substrate are much higher than organic layers and encapsulated air above the OLED. Therefore, if the substrates with high thermal conductivity are used, heat can be efficiently dissipated and temperature distribution in substrate thickness direction would be minimal while the substrates with poor thermal conductivity would show large thermal gradient in the substrate thickness direction.

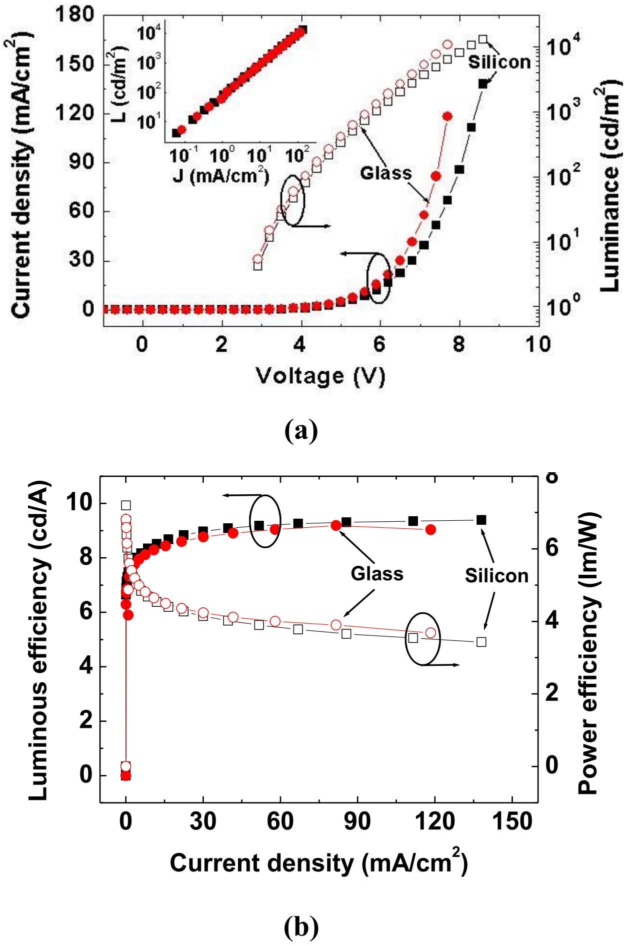
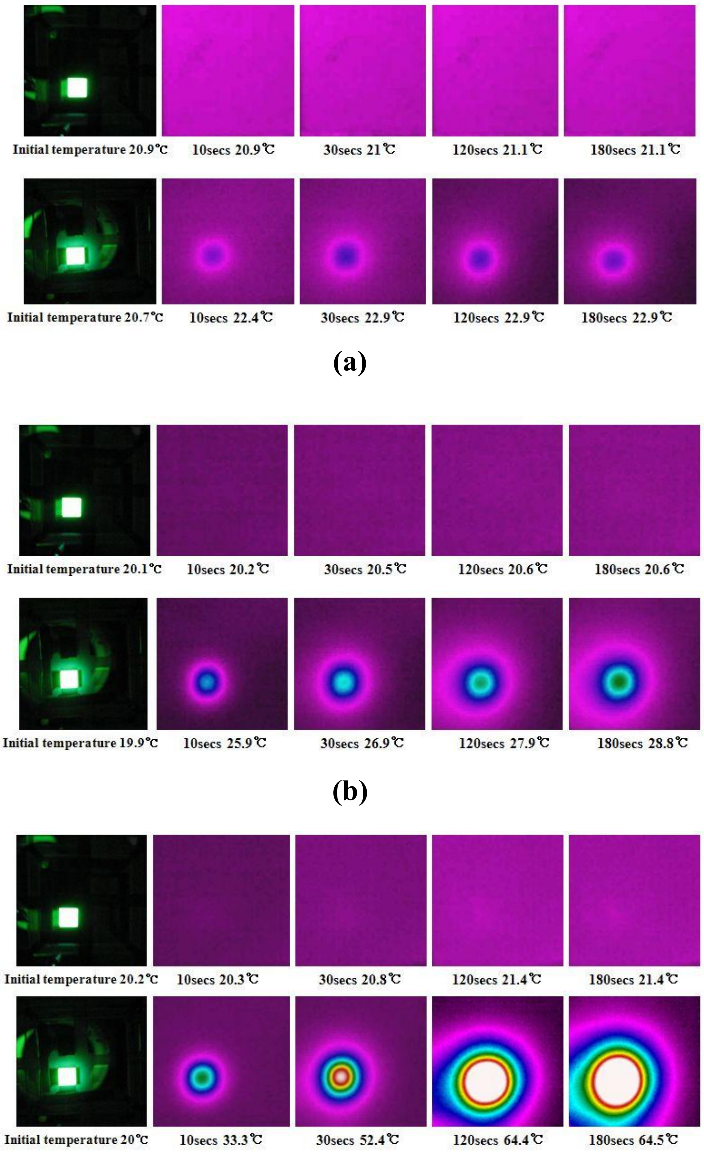


Fig. 1 (a) J-V-L and (b) Efficiency-J characteristics of OLEDs fabricated on silicon and glass substrate



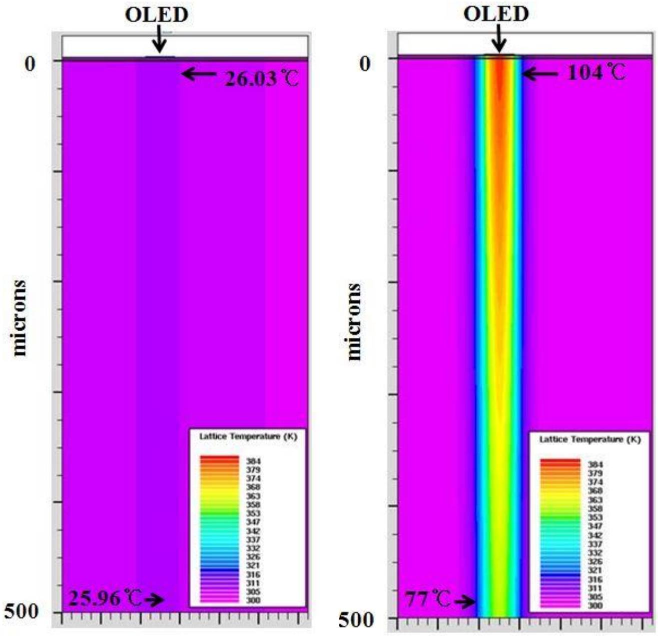
(a)

(b)

(c)

Fig. 2. IR images of heat distribution and peak temperatures at the backside of the silicon (top) and glass (bottom) substrates for first 3 minutes after OLEDs were turned on at luminance levels of (a) 2000, (b) 5000, and (c) 10000 cd/m^2.

Figure.3 shows an example of the simulation result of temperature distribution from OLED anode to the substrate backside for silicon and glass substrates. Simulation was performed by using OLED module of the ATLAS giga simulation tool from Silvaco. As mentioned before, in case of the silicon substrate, there is negligible temperature gradient in the thickness direction, while there is large temperature gradient for glass substrate. Therefore, it is expected that the temperature at the OLED anode can be higher by 20-30 °C than the temperature measured at the substrate backsides. The OLED lifetime can be significantly reduced for glass substrates due to the highly localized thermal stress.



(a) (b)

Fig. 3. Simulation example of heat distribution in the substrate thickness direction for (a) silicon and (b) glass substrates (Same thickness were assumed but it will not much affect the simulated results)

Figure 4 shows lifetime test results for OLEDs fabricated on silicon and glass substrates for three different initial luminance conditions (2000, 5000 and 10000 cd/m^2). As clearly shown in the figure, OLEDs on the silicon substrate showed much longer lifetime, especially at high initial luminance. When OLEDs were operated at 2000 cd/m^2, degradation difference between OLEDs on silicon and glass substrate was very small. However, for luminance of 5000 and 10000 cd/m^2, the degradation differences increased. At high luminance levels, OLED current and input power are exponentially increased and corresponding internal thermal stress will be also increased. However, for silicon wafer, thermal stress is efficiently dissipated through the substrate as shown in Fig. 2, resulting in increased OLED lifetime.

Since OLED layers are very thin, degradation can be easily observed from non-uniform applied electric field distribution, resulting in reduction of the OLED lifetime. Therefore, surface roughness of the bottom anodes can significantly affect the OLED lifetime. In order to make sure that the observed lifetime improvement is mainly from the efficient heat dissipation, we measured the surface roughness of the silver anodes for both silicon and glass substrates. It is noted that the surface roughness of the silicon substrate is generally better than that of the glass substrates. Figure 5 shows the measured AFM results. Surface roughness of 22.6±4 and 26.3±2 nm in peak to valley values, and 2.6±1 and 3.4±1 nm in root mean square (RMS) values, was obtained for the silver anodes on silicon and glass substrates, respectively. From these similar surface properties, we believe that the heat dissipation difference is the main factor for the OLED lifetime improvement in comparison with surface roughness difference in substrates themselves.

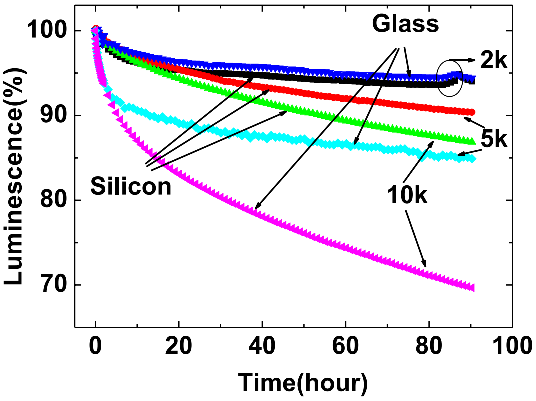
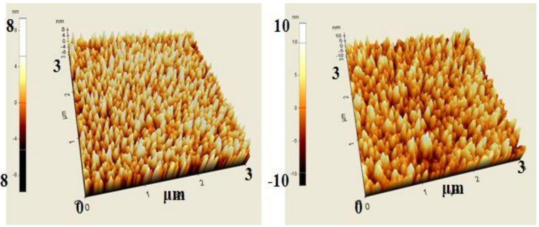


Fig.4. Lifetime test results of OLEDs on silicon and glass substrate for initial luminance of 2000 (2k), 5000 (5k), and 10000 (10k) cd/m^2



(a) **(b)**

Fig. 5. AFM results of bottom silver anodes on (a) silicon and (b) glass substrate: 22.6±4 and 26.3±2 nm in peak to valley values, and 2.6±1 and 3.4±1 nm RMS values were obtained, respectively.

4. Summary

We successfully demonstrated the efficient heat dissipation through the highly-thermally-conductive substrates such as silicon wafer and corresponding OLED lifetime improvement. As the input power and corresponding luminance were increased, we observed that the temperature on backside surface of the substrate with poor thermal conductivity was increased exponentially and thermal stress was accumulated around the OLED area, resulting in large degradation. On the other hand, for the substrate with high thermal conductivity, there was little accumulated thermal stress and corresponding lifetime was longer than that for the poor thermal conductivity substrates. Therefore, it is expected that depending on selection of the substrates, we can achieve extended OLED lifetime for AMOLED or lighting applications.

5. Acknowledgement

This work was supported by SSDIP (SNU-Samsung SDI Display Innovation Program). Authors would like to thank Display Technology Research Center (DTRC), Inter-University Semiconductor Research Center (ISRC), and OLED center at Seoul National University for their utility support.

6. References

1. C. Gärditz and A. Winnacker, *Appl. Phys. Lett.*, 90, 103506 (2007)
2. Xiang Zhou, Jun He, Liang S. Liao, Ming Lu, *adv.Mater*, 12, 4, 265-269 (2000)
3. G. Nenna, G. Flaminio, T. Fasolino, C. Minarini, R.Miscioscia, D.Palumbo, M.Pellegrino, *Macromol. Symp*, 247, 326-332 (2007)
4. M S Xu and J B Xu, *Phys. D: Appl. Phys.*, 37, 1603-1608 (2004)
5. Paulo N.M. dos Anjos, Hany Aziz, Nan-Xing Hu, Zoran D. Popovic, *Org Electron*, 3, 9-13 (2002)
6. George Vamvounis, Hany Aziz, Nan-Xing Hu, Zoran D. Popovic, *Synthetic Met*, 143, 69-73 (2004)
7. Hany Aziz, Zoran D. Popovic, and Nan-Xing Hu, *Appl. Phys. Lett.*, 81, 2, 370-372 (2002)