Easy Process and Performance Improvement for Top-Emission Organic Light-Emitting Diodes by Using UV Glue as the Insulation Layer on Copper Substrate

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***Abstract*—A high heat dissipation material (copper, Cu) was employed as the substrate for top emission organic light-emitting diodes (TEOLEDs). The UV glue was spin-coated onto the Cu substrate as the insulation layer to effectively improve Cu surface roughness and reduce process complexity. From the optoelectronic results, the optimized device with the Cu substrate shows the maximum luminance of 14110 cd/m^2 and luminance efficiency of 7.14 cd/A. The surface and junction temperatures are measured to discuss the heat-dissipating effect on device performance. From the results, TEOLED fabricated on a Cu substrate has lower junction (55.34 °C) and surface (25.7 °C) temperatures, with the lifetime extended seven times. We employed Cu foil as the substrate for flexible TEOLED with maximum luminance of 10310 cd/m^2 and luminance efficiency of 7.3 cd/A obtained.**

***Index Terms*—Heat dissipation, junction temperature, lifetime, luminance efficiency, organic light-emitting diode (OLED), UV glue.**

I. INTRODUCTION

THE organic light-emitting diode (OLED) [1] is a new-generation flat panel display with the advantages of self-luminescence, wide viewing angle ($> 170°$), prompt response time ($\sim 1\ \mu$s), low operating voltage ($3 \sim 10$ V), high luminance efficiency, and high color purity that can be produced easily on various substrates. In recent years, much larger OLED displays sizes have been fabricated. These large monitors must be driven using thin-film transistors (TFTs) that have even brightness, higher resolution, and longer life. Traditional OLED resolutions are conducted mostly in the bottom emission structure and tend to be blocked by bottom TFTs and data lines, affecting ray penetration to the bottom. Top-emission OLED research has become inevitable for enhancing the opening rate [2], [3].

In this study, a high heat dissipation coefficient substrate (Cu: 401 W/m $\cdot$ K) [4] is used to fabricate top-emission OLEDs (TEOLEDs). The heat-dissipation substrate will improve the OLED lifetime and performance. However, a copper (Cu) substrate surface is not completely smooth and will usually have spikes. After the OLED devices are evaporated onto the Cu substrate, the spikes will still exist. When the device is operated under high current density, a heavy amount of current density will concentrate at the spikes, leading to point discharge and damage to the device by causing the device to short circuit, generating joule heat [5]. The luminance efficiency and device lifetime will therefore be reduced. To improve the Cu substrate surface roughness, UV glue was spin-coated onto the Cu substrate as the insulation layer to effectively smooth the surface and significantly improve TEOLED lifetime and performances.

In addition, Xi *et al.* have demonstrated that the diode forward voltage can be used to assess the junction temperature of "p–n junction diodes" [6]. The forward voltage method consists of two series of measurements: a calibration measurement and the actual junction–temperature measurement. The OLED is also a p-n junction diode, and the joule heat are generating at the interface of each layer during device (LED or OLED) operations. For this reason, the forward voltage method can be employed to measure the junction temperature of OLEDs.

Previous papers have reported that OLEDs fabricated onto flexible substrates using amorphous and TFTs onto flexible metal foils have propelled the development of flexible active matrix OLEDs (AMOLEDs) or active matrix polymer LEDs (AMPLEDs) displays [7]–[10]. Chuang *et al.* reported that the metal foils are particularly attractive for AMOLED or AMPLED displays because they are excellent barriers to water and oxygen which degrade the lifetime of these displays [7]. Hence, we fabricated the TEOLED device onto a flexible Cu foil substrate with spin-coated UV glue as the insulation layer.

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II. EXPERIMENTAL

The OLED devices are generally fabricated onto glass and Cu substrates (39 mm × 39 mm × 0.5 mm). The heat transfer coefficient of Cu (purity: 99.9%), glass, and UV glue are 401, 1 [11], and 0.5 $\mathrm{W/m \cdot K}$ (supplied by Material and Chemical Research Laboratories, Industrial Technology Research Institute), respectively. Before depositing the metal anode, the substrate is cleaned ultrasonically with neutral cleaning agent (8 min), methanol (8 min) and deionized water (DI-Water) (8 min). The substrate is then dried via blown nitrogen and then placed into an oven for heating at 90 °C for 10 min. The UV glue is then spin-coated onto the Cu substrate and cured using UV light for 10 s. The prepared substrate is next placed into a metal evaporation chamber; with Al (with high-reflectivity) and Au (with high work function) deposited under 4×10^{-6} torr to create an anode. The substrate is then moved into an organic evaporation chamber for organic thin-films deposition under 2×10^{-6} torr. The hole-injection layer (HIL) is made of 4,4',4''-tris(N-3-methphenyl-N-phenyl-amino)-triphenylamine (m-MTDATA), the hole transport layer (HTL) is N,N'-Bis(naphthalen-1-yl)-N,N'-bis (phenyl)–benzidine (NPB), and the emitting and electron transport layer (EML/ ETL) is tris(8-hydroxy-quinolinato)aluminum (Alq3). The device is next moved back into the metal evaporation chamber for metal cathode LiF/Al/Ag (semi-transparent) deposition. The total semi-transparent film thickness does not exceed 20 nm. The device active area is 36 mm^2. After the device was fabricated, the SpectraScan PR650 and Keithley 2400 were employed to measure the optoelectronic characteristics. An infrared camera NEC TH9100 was employed to measure the substrate backside temperatures and thermal distribution images.

III. RESULTS AND DISCUSSION

UV glue is spin-coated onto the Cu substrate (39 mm × 39 mm × 0.5 mm) using various rotation speeds to apply the UV glue evenly onto the substrate to create a flat Cu substrate surface. The UV glue also serves as the insulation layer. The insulation layer thickness is measured using α-step. When the rotation speeds were 4000, 5000 and 6000 rpm, fixed at 10 s, the UV glue film thicknesses were 8.63, 7.10, and 5.96 μm. Moreover, the surface roughness ($\mathrm{Rms} = 0.312$ nm) of glass with spin-coating UV glue is smoother than the bare glass substrate ($\mathrm{Rms} = 1.07$ nm), and the performances of device with UV glue were better than those without UV glue (as shown in Figs. 1 and 2). Hence, UV glue was also applied onto a glass substrate for comparison. At a rotation speed of 6000 rpm, fixed at 10 s, the UV glue film thickness on the glass substrate was 6.20 μm. At rotation speeds of 4000 and 5000 rpm, the insulation layer is too thick. The Cu substrate surface is filled but the insulation layer surface is not smooth. The AFM images of insulation layer (UV glue) surfaces on the Cu substrate with different rotation speeds are shown in Fig. 3. When the rotation speed was increased to 6000 rpm, the insulation layer was thinner and the surface roughness decreased from 2.279 to 1.711 nm. Fig. 1 shows the luminance–current density (L–J) and Fig. 2 the luminance efficiency–current density (Y–J) characteristics for different rotation speeds and substrates. The thinner insulation spin-coated onto the Cu substrate produced the maximum luminance 14110 cd/m^2 and maximum luminance efficiency 7.14 cd/A.

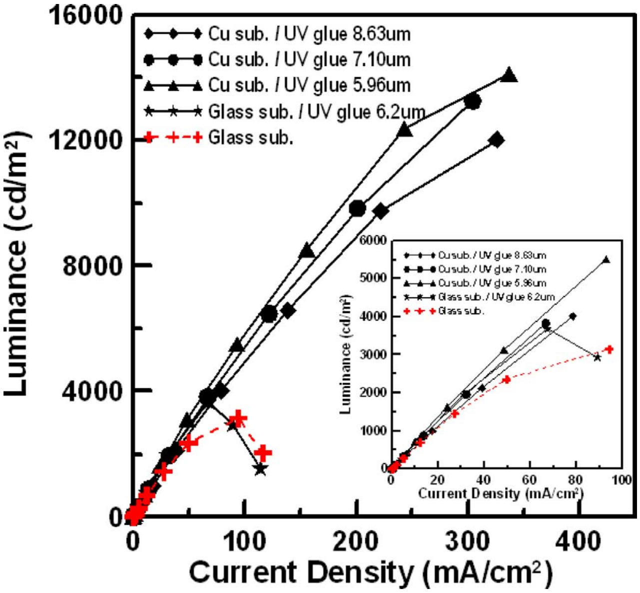

Fig. 1. L-J characteristics for different rotation speeds and substrates.

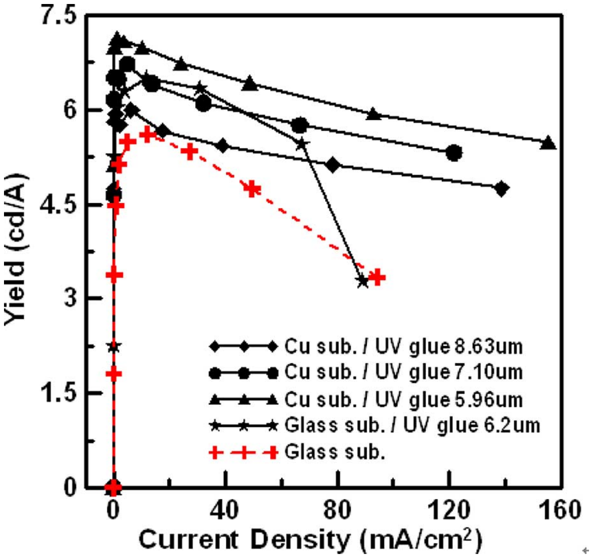

Fig. 2. Y–J characteristics for different rotation speeds and substrates.

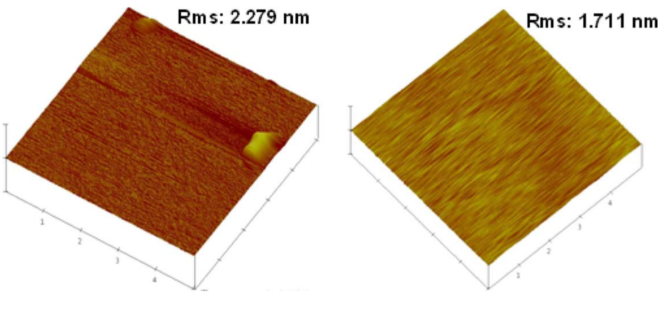

Fig. 3. AFM images of insulation layer (UV glue) surfaces on the Cu substrate with different rotation speeds of: (a) 4000 rpm and (b) 6000 rpm.

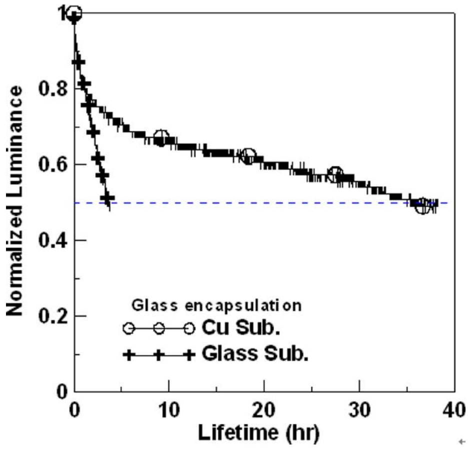

Fig. 4. Lifetime test of TEOLEDs with glass and Cu substrates.

Comparing the device characteristics between Cu and glass substrates (as shown in Figs. 1 and 2), devices fabricated onto a Cu substrate have better optoelectronic characteristics than those spin-coated onto glass substrates. We also found that the luminance and luminance efficiency (as shown in the inset of Figs. 1 and 2) of the devices with thicker insulation layer onto Cu substrate were lower than for device with thinner insulation layer on glass under low current density ($< 80\ \mathrm{mA/cm^2}$). The reason is that the insulation layer surface is still rough when the insulation layer is too thick, leading to decreased TEOLED performance. However, the insulation layer surface roughness could be improved by decreasing the insulation layer thickness. Although a device with a thinner insulation layer has better luminance efficiency than devices with thicker insulation layers on Cu substrates under low operating conditions, the luminance efficiency decays quickly and breaks down under high current density. This is because the Cu substrate has a better heat conductivity coefficient (401 W/m · K) than the glass substrate (1 W/m·K). The joule heat can be dissipated quickly by the Cu substrate, preventing breakdown under high current density. From the lifetime tests shown in Fig. 4, the device lifetime when fabricated on a Cu substrate is seven times longer than that of device fabricated onto glass. This is attributed to the Cu substrate effectively dissipating joule heat, preventing organic material recrystallization.

To understand the joule heat effect on device performance, we measured the surface and junction temperatures [12], [13] of devices with different substrates. Table I shows the surface and junction temperatures of devices with Cu and glass substrates. When the operating current is increased, the surface temperature of the glass substrate increases. The reason is that when the operating current is increased, a huge mass of joule heat accumulates at the device active area (with glass substrate), leading to the surface temperature increasing substantially. Conversely, the surface temperature of the Cu substrate exhibits only a small temperature increase because the joule heat is effectively dissipated by the Cu substrate. Comparing the highest surface temperatures of glass (57.8 °C @ 40.98 mA) and Cu substrate devices (25.7 °C @ 121.32 mA), the surface temperature of Cu substrate can be kept from 23 °C to 26 °C, prevented device breakdown.

TABLE I
MEASUREMENT SURFACE AND JUNCTION TEMPERATURES OF DEVICES WITH CU AND GLASS SUBSTRATES

substrate	operating current (mA)	Luminance (cd/m^2)	temperature of device surface (°C)	junction temperature (°C)
glass	11.11	1956	29.1	41.48
	24.26	3676	34.2	55.08
	32.09	2930	46.4	63.18
	40.98 (max.)	1552	57.8	72.38
Cu	3.63	706	23.2	30.76
	17.50	3126	23.5	33.65
	33.43	5517	24.1	36.98
	121.32 (max.)	14110	25.7	55.34

max.: the maximum operating current value before device breakdown

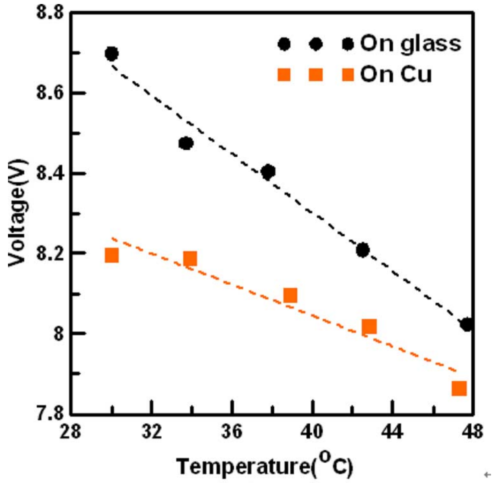

Fig. 5. K curves for TEOLEDs with glass and Cu substrates.

To measure the TEOLEDs junction temperatures [6], [14], the devices were placed within a constant temperature oven to control the initial environmental temperature T_{initial} ($\mathrm{T_i} = 30°\mathrm{C}$), and measure the corresponding forward voltage V_{Fi}. The temperature was then increased to T_{high} ($T_{\mathrm{h}} = 50\,°\mathrm{C}$). Each time, the temperature was increased 5 °C in 5 min and then held for 6 min to reach a thermally stable status. During the 6-min temperature maintenance process, the device forward voltage (V_{F}) under the maintained temperature was measured every 3 min. The measured device current was 0.01 mA. Fig. 5 shows the K factor measured curves of for devices with glass and Cu substrates, respectively. The calculated K factor values were automatically fitted using grapher software (dashed line). The following equation was used for the calculation [12]–[14]:

$$K = \left| \frac{T_{\mathrm{h}} - T_{\mathrm{i}}}{V_{\mathrm{Fh}} - V_{\mathrm{Fi}}} \right|. \tag{1}$$

From the results, the K curve slope for the Cu substrate device was more gradual than that for the glass substrate device. This proved that the Cu substrate could effectively dissipate the heat.

Therefore, the V_F for the Cu substrate device decreased less than that for the glass substrate device.

After K curve measurement, a constant measuring current ($I_M = 0.01$ mA) was then applied to the device to measure the corresponding forward voltage (V_{F0}). A high operating current was then applied (heating current, I_H). Once the device was operated for a while and the substrate temperature turned stable, the operating current (I_H) was switched to I_M, and its corresponding forward voltage V_{FSS} was measured. T_{J0} is the device's initial temperature prior to measurement (the environmental initial temperature was assumed to be 30 °C in this study). Once the above values were obtained using [12]–[14]

$$\begin{aligned} \Delta T_J &= K \times \Delta V_F \\ \Delta V_F &= |V_{F0} - V_{FSS}| \\ T_J &= T_{J0} + \Delta T_J \end{aligned} \tag{2}$$

the junction temperature (T_J) could be calculated for the device under the operating current (I_H):V_{Fh} is the relative forward voltage at maximum temperature (50 °C) at operation current 0.01 mA; V_{Fi} is the device's forward voltage at initial temperature (30 °C).

Table I shows a comparison of the junction temperatures for devices with Cu and glass substrates for different operating current (mA) conditions. The results show that when the glass substrate device was operated at 32.09 mA, the junction temperature was 63.18 °C. When the Cu substrate device was operated at the similar current of 33.43 mA, the junction temperature was only 36.98 °C. After comparing the junction temperatures of the Cu and glass substrate devices, lower junction temperature for the device with the Cu substrate could be obtained under a similar operating current. This proved that the Cu substrate indeed could dissipate the heat effectively and quickly prevent breakdown.

We also employed Cu foil as the substrate for a flexible TEOLED to reduce the influence of joule heat. UV glue was spin-coated onto the Cu foil as an insulation layer to improve the foil surface roughness. The flexible TEOLED has a maximum luminance of 10310 cd/m^2 and luminance efficiency of 7.3 cd/A.

IV. CONCLUSION

A high heat-dissipation material (Cu) was successfully used as the substrate for a TEOLED. The Cu substrate reduces the influence of joule heat from devices operated under high current density. UV glue was spin-coated onto the Cu substrate as the insulation layer to effectively improve the roughness and reduced process complexity, providing significantly increased device lifetime and performance. At a rotation speed of 6000 rpm (10 s), the maximum luminance and efficiency were 14110 cd/m^2 and 7.14 cd/A. From the Y–J characteristic, the device luminance efficiency with a Cu substrate decayed slowly. We demonstrated better heat dissipation ability with a Cu substrate by comparing the thermal distribution images of TEOLED devices with Cu and glass substrates. The Cu substrate device surface temperature could be held to 25.7 °C under high current density without breakdown. The surface temperatures of the glass substrate device increased from 29.1 °C to 57.8 °C when the junction temperature increased. From the junction temperature test, the device with the Cu substrate had lower junction temperature than the device with glass substrate under similar operating current. The Cu substrate device lifetime was about seven times longer than that for devices on glass substrates. We demonstrated that the Cu heat dissipation material can effectively dissipate joule heat and significantly improve the device performance and lifetime. Finally, we employed Cu foil as the substrate for flexible TEOLED and spin-coated UV glue onto the foil substrate as the insulation layer. The flexible TEOLED showed maximum luminance of 10310 cd/m^2 and luminance efficiency of 7.3 cd/A.

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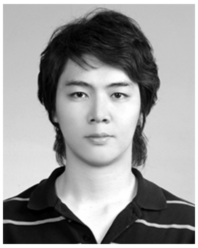

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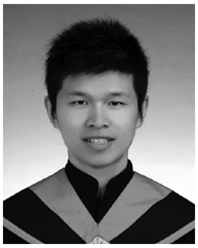

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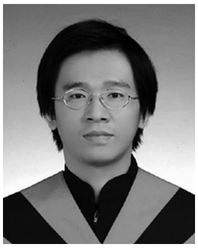

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