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# Top-emitting organic light-emitting diodes integrated with thermally evaporated scattering film for reducing angular dependence of emission spectra

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ABSTRACT

A scattering film is obtained by thermally evaporating tetraphenylethene (TPE) onto the substrate. The TPE molecules self-crystallize themselves as microsheet on reaching the substrate. The resultant TPE films exhibit strong light scattering effect because of the random distribution of the crystallized sheets. The scattering films, being able to be deposited by thermal evaporation, can thus integrate with top-emitting organic light-emitting diodes (OLEDs) directly. As a result, the top-emitting OLEDs exhibit reduced angular dependence of emission spectra; for example, the color coordinates is only slightly shifted from (0.2891, 0.6001) to (0.2735, 0.5617) when the viewing angle increases from 0° to 80°.



## 1. Introduction

Top-emitting structures with light emitted from the top surface are preferred for active-matrix organic light-emitting diode (AMOLED) displays, because they promise larger aperture ratio and can be deposited on opaque substrates [1,2]. The top-emitting OLEDs, with organic layers sandwiched between a reflective bottom electrode and a semi-transparent top electrode, can be optically treated as an Fabry-Pérot cavity. In such configuration, light reflected from the bottom electrode and that from the top electrode interfere with each other. If the effective length of the cavity satisfies $L_{\text{eff}} = m\frac{\lambda}{2}$ (where $m$ is an integer), the emission is strengthened [2]. By setting the cavity length resonant with the emission wavelength, the top-emitting OLEDs can exhibit higher efficiency and purer color compared with their bottom-emitting counterparts [3,4]. However, the effective cavity length is angularly dependent which is determined by $L_{\text{eff}}(\theta) = L_{\text{normal}} \times \cos\theta$, where $\theta$ is the viewing angle [5]. As viewing angle increases, the effective length is reduced, which results in a smaller resonant wavelength and thus a bluer emission color. Therefore the top-emitting OLEDs generally exhibit poor viewing characteristics; i.e., the emission color is highly dependent with the viewing angle. This problem can be solved by reducing the reflectance of the top electrode, for example, using a capping layer or employing electrode with high transparency [6–10]. Although effective, it is at the cost of losing color saturation due to the weakened interference.

To solve the trade-off between color saturation and color angular stability, one clever way is equipping the top-emitting OLEDs with a diffusing film [11–17]. Light from different angle can be effectively scattered by the diffusing film, thus reducing the angular dependence of emission. To compatible with the fabrication process of top-emitting OLEDs, ideally, the scattering film should be deposited by thermal evaporation. In this regard, most proposed scattering structures, either deposited by wet-coating [12,13] or prepared by photolithography [14,15], cannot integrate with top-emitting OLED directly due to their incompatible and complex fabrication process. In this work, we develop a tetraphenylethene (TPE)-based scattering film which can integrate with top-emitting OLEDs directly. We have previously found that TPE molecules are easily self-crystallized due to their low $T_g$. The thermally deposited TPE scattering film was previously exploited as light extraction layer for bottom-emitting OLEDs [18,19]. In this work, we investigate its role as a top capping layer for reducing the angular dependence of emission spectra of top-emitting OLEDs. Our results show that the color angular stability can be greatly improved by equipping the top-emitting OLEDs with a 300 nm top scattering layer.

## 2. Experimental

The TPE scattering films were deposited by thermal evaporation under a base pressure of $5 \times 10^{-4}$ Pa. The morphologies of the

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scattering films were characterized by JEOL-JSM-6490 SEM (scanning electron microscopy). To characterize the scattering effect of the films, the HAZE of the scattering films was determined by measuring the total transmission and the specular transmission using an Ocean Optics USB2000+ spectrometer and an integrating sphere. To evaluate its role as a top scattering layer, top-emitting OLEDs with structures glass/Al 100 nm/HATCN 35 nm/NPB 15 nm/Alq 50 nm/Yb 5 nm/Ag 20 nm (Where HATCN, NPB, Alq, Yb work as hole-injector, hole-transporter, light-emitter/electron-transporter, electron-injector, respectively.) were first fabricated, followed by depositing a 300 nm TPE on top of the devices. For comparison, devices without TPE top scattering layer were also fabricated. The structures of the devices and the molecular structure of TPE are shown in Fig. 1. The angular dependence electroluminescent (EL) spectra of the devices were measured by a PR670 spectrometer and a rotating stage. The current density ($J$)–voltage ($V$)–luminance ($L$) characteristics of the devices were measured by a keithley 2614B source meter and a calibrated UDT PIN-25D silicon photodiode.

## 3. Results and discussion

The morphology of the top electrode was characterized first. Fig. 2(a) shows the photos of the top electrode. Without scattering film, the 20 nm Ag is semi-transparent, whereas by depositing 300 nm TPE on top of the Ag, the film exhibits a milky appearance. Light is strongly diffused by the TPE particles, and thus the image behind the film cannot be clearly observed. Closer observation using SEM found that the film is composed by numerous microsheets, as shown in Fig. 2(b). These microsheets are probably resulted from the self-crystallization of TPE molecules. The TPE molecules can self-assemble themselves in the form of microsheets even in room temperature, which is probably due to its low $T_g$ [18]. At room temperature, the TPE molecules may acquire enough thermal energy to adjust their position and fit themselves into their crystalline lattice. Similar phenomena have also been observed for other low $T_g$ materials such as BCP, BPhen or TPD [20–22]. Crystallization can be detected when thin films based on these low $T_g$ materials are stored in vacuum or in air for tens of hours [20–22]. The crystallization process can be accelerated by annealing the films. The advantage of TPE over these reported materials is its faster crystallization process, which occours as soon as it reaches the substrate under the room temperature environment. Due to the random distribution of the TPE microsheets, the resultant films can scatter the light effectively.

To further characterize the light scattering ability of the films, the HAZE of the films was measured. Fig. 3(a) shows the total

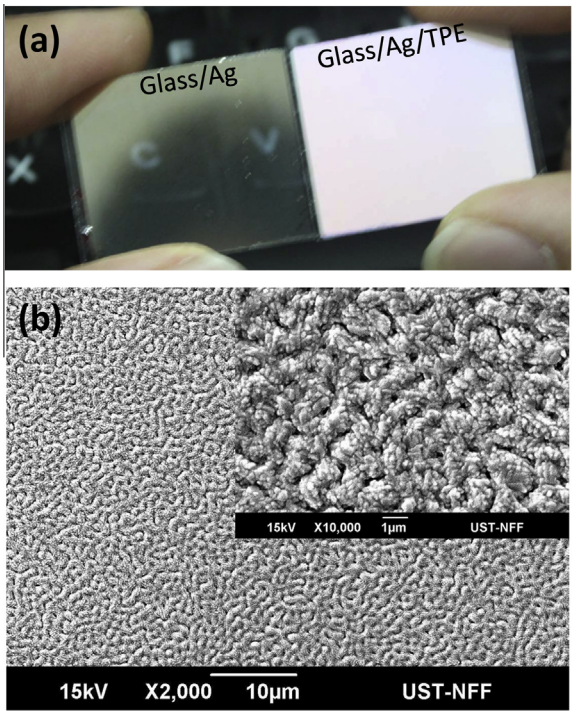


**Fig. 2.** (a) Photos of the top electrodes, (b) SEM images of the top electrode with 300 nm TPE scattering layer.

transmission spectra of the films, which were measured by using an integrating sphere that collects all of the transmitted light. All films exhibit a high total transmission of ~90%, since TPE does not absorb the visible light. However, the specular transmission, which measures the amount of directly transmitted light, is significantly lower than that of the total transmission, indicating that most transmitted light is diffused by the TPE microsheets. As shown in Fig. 3(b), the specular transmission is decreased when the thickness of TPE is increased from 100 to 300 nm. No further improvement has been observed when the thickness is above 500 nm. The HAZE indicates what percentage of light is scattered is calculated by HAZE $= \frac{T_{total}-T_{specular}}{T_{total}} \times 100\%$. As shown in Fig. 3(c), the films with 300 nm TPE exhibit the highest HAZE. At a wavelength of 520 nm, it exhibits a HAZE of 37%, which indicates that 37% of the light is scattered by TPE and this value is higher than 29% and 24% for the films with 200 and 100 nm TPE, respectively. Because of the strong wavelength dependence ($\sim\lambda^{-4}$) of the

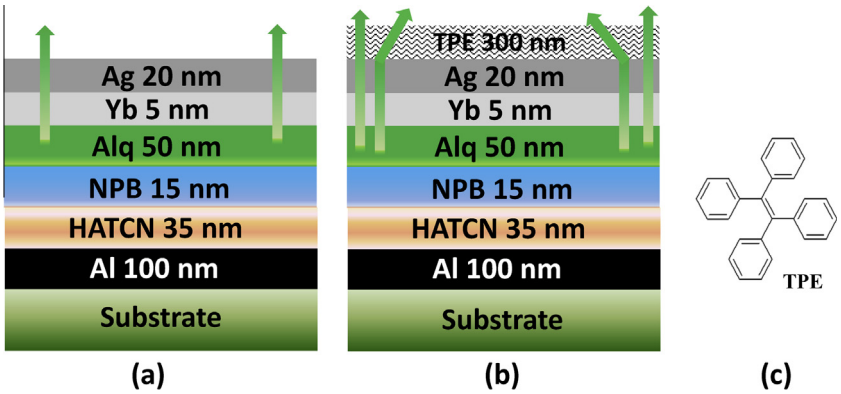


**Fig. 1.** Structure for the devices without (a) and with (b) TPE top scattering layer, and molecular structure of TPE (c).