Microstructure and device performance of thin film light emitting polymers

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Abstract

In this paper, the performance of polymer light emitting diodes (PLEDs) was investigated and related to their thin film morphology. Two methods were used to cast the thin film, i.e. spin coating and dip coating. The film morphology was controlled by different film formation conditions, e.g. spin speed and withdrawal speed, as well as different solution properties, e.g. polymer molecular weight and solvent. Phase separation was inspected using both optical microscopy and an atomic force microscopy. The device performances of interest were characterised by measuring optical response, the Commission Internationale de l'Eclairage Chromaticity, electrical characteristics, and device lifetime. The study has established that a high efficiency PLED can be achieved by using a blend of electron transporting emitter and a hole transporting polymer. The device prepared from the blend shows a low turn-on voltage, a large current density, a high efficiency, and an acceptable lifetime. The result shows that light emitting polymer film morphology is crucial in determining the device performance. As solvent evaporation rate increases, phase separation reduces to a fine-scale. The device efficiency decreases with a reduction of degree of phase separation while the lifetime enhances. It is likely that there is an optimum degree of phase separation for device optimisation (high efficiency and long lifetime). In addition, it was established that both dip and spin coating were effective fabrication processes.

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1. Introduction

Polymer light emitting diodes (PLEDs) are making a transition from a laboratory scale to an industrial level and an understanding of the effect of processing on device performance is now paramount. The device performance is mainly concerned with four factors, namely, (i) device efficiency and brightness, (ii) power consumption, (iii) device lifetime, and (iv) colour control [1]. The structure of the PLEDs shown in Fig. 1 consists of several elements, i.e. an emissive component (light emitting polymer, LEP), a hole transporting layer (poly(3,4-ethylenedioxythiophene) doped with polystyrene sulphonic acid, PEDOT:PSS), and two electrodes (indium–tin oxide anode and metal cathode); therefore, achieving good device performance depends on several issues, such as electrode characteristics, polymer/electrode interfacial effect, and LEP morphological and optoelectronic properties.

Accomplishing balanced electron-hole injection and perfect recombination of the charge carriers would ensure the optimum performance of PLEDs. Various approaches have been introduced to control charge injection and charge balance, such as appropriate selection of anode and cathode, surface modification of the electrodes, insertion of hole-injection layers, and use of heterostructure or polymer blends. For an effective hole injection, the anode should have a relatively large work function matching the highest occupied molecular orbital (HOMO) level of the LEP, whereas the cathode should have a low work function to ensure effective electron injection into the lowest unoccupied molecular orbital (LUMO) level of the LEP. Indium–tin oxide (ITO) has proved to be a suitable anode [2–4]. However, Scott et al. [5] found that ITO acts as a source of oxygen which leads to oxidation causing device aging; therefore, the insertion of the hole-injection transporting layer is necessary to avoid the direct contact between the emissive LEP layer and ITO as well as to enhance the balanced charge injection [6–9]. Low work function metals (e.g. calcium and magnesium) are suitable for the electron injection electrode (cathode). However, these materials, in
particular, calcium, are highly reactive and therefore very susceptible to oxidation, causing the device instability [10]. In order to improve the device stability, the cathode is often capped with atmospherically stable metals, e.g. aluminium and silver [11–14].

This particular study focuses on the processing and morphology of the LEP layer. Other parameters of the device construction have been kept strictly identical in order to facilitate comparison.

Polymer blends can broaden emission spectra, alter the electronic properties, and improve the device performance [15,16]. Such aspects are an outcome of changes in the structure of the thin films. Consequently, an understanding of the mechanism that affects the morphology of the LEP film is crucial and beneficial to PLED manufacture. Phase separation often occurs when using blends of LEPs containing monomers of significantly different chemical structures. Various techniques have been used to study the morphology of the LEP film [17–19]. However, very little information about the relationship between the morphology of the emissive LEP film and the device performance is available. Cina studied the PLED performance prepared from blends of hole-transporting polyfluorene (poly(9,9-dioctylfluorene)-co-TFB) and poly(9,9-dioctylfluorene-co-benzothiadiazole) (F8BT) and found that increasing the polymer molecular weight results in large-scale phase separation, however the device efficiency also increases. The polymer blends used in this paper are similar to those studied by Cina, Morgado [17], and Kim et al. [20] where TFB or poly(9,9-dioctylfluorene) is replaced by Host 1 (a poly(9,9-dioctylfluorene–TFB copolymer).

2. Materials and device fabrication

Three LEP solutions used were blends of two different LEP systems, which are poly(9,9-dioctylfluorene-co-benzothiadiazole) (F8BT) and poly(9,9-dioctylfluorene-co-TFB) (Host 1), with a weight ratio of approximately 5:95. Mixed isomers xylene was used as a solvent and the blends were made at the concentration of 1.6% w/v (1.6 grams of polymer dissolved in 100 ml of solvent). Details of the solutions with a degree of polymerisation (DP) of the LEPs are summarised in Table 1. A reference solution (solution 4), which was used at the Cambridge Display Technology, was prepared from the blend of Host 1 and F8BT at the concentration of 1.2% w/v using toluene as a solvent. Due to confidentiality, DPs of the polymer system cannot be revealed.

A 25 × 25 mm² commercial patterned ITO-coated glass was used as a substrate. The substrate was patterned to form 8 pixels with the area of each pixel of 2 × 12 mm². Prior to the fabrication process, the substrates were cleaned by oxygen plasma. The 50 nm thick hole-injection-transporting layer of PEDOT:PSS was prepared using a spin coating process [21]. After the coating process, the substrate was baked on a hot plate for 10 min to dry the PEDOT:PSS layer. A uniform LEP film of approximately 70 nm thick was coated on top of the PEDOT:PSS layer immediately by a spin or dip coating process. For the spin coating process, a spin coater used was a Karl Suss RC 8 GYRSET, which can operate with a rotating cover called a GYRSET. The GYRSET system is a closed chamber that creates a solvent-rich environment above the substrate. The evaporation rate of the polymer solution can thus be controlled by the use of the GYRSET. The spinning with GYRSET is henceforth referred to as ‘slow evaporation’ whereas the spinning without GYRSET is referred to as ‘fast evaporation’. For the dip coating process, a Stable Microsystems Texture Analyser (TA-XT2) was used in the experiment for the dip coating process and two drying methods were applied to the polymer films, i.e. ambient drying and hot-air drying, in order to investigate the effect of solvent evaporation. For ambient drying, the substrate was left in a vertical orientation in a fume cupboard for 60 min to dry. For hot-air drying, hot air from a hair dryer was blown onto the substrate during the withdrawal process. A diffuser was attached to the head of the hair dryer to achieve uniform distribution of the hot air. The hot air had a temperature of around 50–60 °C and the blowing speed was approximately 6 m/s. The aim of hot-air drying is to minimise the overlap between the liquid draining and film drying stages, which can cause a non-uniform film thickness. In the following discussion, the ambient drying and hot-air drying are referred to as slow and fast drying, respectively. The spin and withdrawal speeds were adjusted accordingly in order to obtain the film thickness of approximately 70 nm. Details in relation to the relationship between film thickness and spin and withdrawal speeds as well as the film thickness measurement can be found from Yimsiri and Mackley [21].

![Diagram of PLED structure](image)

**Fig. 1. Basic structure of PLEDs.**

**Table 1** Details of LEP solutions

<table>
<thead>
<tr>
<th>Solution</th>
<th>Host 1 (DP)</th>
<th>F8BT (DP)</th>
<th>Concentration (% w/v)</th>
<th>Solvent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>52</td>
<td>108</td>
<td>1.6</td>
<td>Xylene</td>
</tr>
<tr>
<td>2</td>
<td>52</td>
<td>295</td>
<td>1.6</td>
<td>Xylene</td>
</tr>
<tr>
<td>3</td>
<td>163</td>
<td>295</td>
<td>1.6</td>
<td>Xylene</td>
</tr>
<tr>
<td>4*</td>
<td>–</td>
<td>–</td>
<td>1.2</td>
<td>Toluene</td>
</tr>
</tbody>
</table>

*Solution 4 is a reference solution.*
After the deposition of the emissive film, the substrate was kept in an opaque box immediately prior to subsequent cathode evaporation to prevent exposure to light, humidity, and contamination by dust. Calcium was used as a cathode because it has a low work function to match the LUMO level of the polymer. The deposition of the cathode was done by a thermal evaporation at $10^{-4}$ Pa to achieve the thickness of 50 nm. A protecting layer of aluminium of at least 500 nm thick was capped on the calcium layer using the same method. Finally, metal legs were assembled and the device was encapsulated using a glass cover slide with the same size of $25 \times 25$ mm$^2$ and epoxy resin. After the encapsulation, the device was kept in a glove box for at least 12 h to allow the epoxy glue to set before performing any tests. Both metal leg assembling and encapsulation processes must be carried out under a dry nitrogen atmosphere in the glove box. At least ten devices were made from the same material and fabrication process to ensure the reproducibility.

3. Morphological characterisation

Phase separation was investigated using an Olympus BX60 optical microscope as well as a Digital Instruments atomic force microscope (AFM). In order to achieve the best possible contrast between phases with the optical microscope, a 488 nm wavelength light source was used to excite the thin films. This wavelength can be absorbed by F8BT, but not by Host 1 (see absorption spectra in Fig. 2). Therefore, the wavelength can selectively excite F8BT, leading to the appearance of bright and dark areas according to their enrichment in F8BT as shown in Fig. 3(a). A Charge-Coupled Device (CCD) camera was attached to the microscope to obtain digital images. Several images were taken from different areas of the film and the images were analysed using a Scion Image software. The Scion Image is a PC version of the NIH-image software, which is a public domain image processing and analysis programme developed by the U.S. National Institutes of Health. This software uses the grey-scale to distinguish the area of interest from the background as shown in Fig. 3(b) and it can be used to measure area, diameter, perimeter, length, ellipse major axis, and ellipse minor axis of user defined regions. The degree of F8BT-rich phase was of interest and used to quantify the level of phase separation. As a result, the area ratio of the bright phase to the total area was determined using the software. An average value of the area ratios from several images was used to represent the phase ratio of an individual film. A higher F8BT-rich phase ratio indicates a higher degree of phase separation.

The analysis using the AFM was also carried out on some samples to verify the results of the optical microscopy at a higher resolution. The AFM used is a Dimension 3100 linked to a NanoScope III controller from Digital Instrument (Veeco Instruments). For each film, the areas of $1 \times 1$ and $10 \times 10$ μm$^2$ were scanned using the tapping™ mode at an engagement set point of 2 Volts to minimise damage to the samples [22]. Single crystal silicon tip with a spring constant of 60 N m$^{-1}$ was used. In these experiments, the scan rate and number of samples used were 0.5 Hz and 512, respectively for $1 \times 1$ μm$^2$ scans and 1 Hz and 512, respectively, for $10 \times 10$ μm$^2$ scans. The RMS roughness is the standard deviation of the height of the surface, which is given by:

$$\text{RMS} = \sqrt{\frac{\sum_{i=1}^{N} (Z_i - Z_{avg})^2}{N}}$$ (1)
where $Z_{\text{avg}}$ is the average of the height ($Z_i$) and $N$ is the number of points within a given area. The RMS roughness values of the base line noise in these experiments are around 0.01–0.05 nm.

The bright areas shown in a 2-D topographic AFM image (Figs. 5 and 7) are the F8BT-rich phase, corresponding to the bright areas in the microscopic image (Fig. 3(a)), whereas the dark area is the continuous phase.

4. Microstructure of LEP films prepared by spin coating process

Fig. 4 is a plot of the F8BT-rich phase ratio and the film thickness as functions of spin speed of solution 1 at different solvent evaporation rates. The F8BT-rich phase ratio decreases as the spin speed increases, which is similar to the relationship between film thickness and spin speed. This is a result of a higher solvent evaporation rate at a higher spin speed. For the spinning with GYRSET, the degrees of phase separation are relatively constant when the spin speeds are between 500–1500 rpm. At 2000 rpm, the film microstructure changes from a large scale to a fine scale phase separation, resulting in a significant reduction of the phase ratio. At spin speeds higher than 2000 rpm, the F8BT-rich phase ratio levels off. The limited degree of phase separation at high spin speeds might be because the quench time is very fast and the limit solvent concentration, where the morphology of the film does not change with further decrease in the concentration, is reached quickly. The results from the spinning without GYRSET also show a similar trend, but the phase ratio gradually decreases with the spin speed rather than a sharp decrease. This is because with the GYRSET, the evaporation rate is high even at slow spin speeds. It is also found that the degree of phase separation increases with polymer concentration and polymer molecular weight.

It is noted that although the polymer solutions used compose of F8BT:Host 1 of 5:95 (F8BT ratio is approximately 0.05 by volume), some of values of the F8BT-rich phase ratio are higher than 0.05. This is because the ratio is calculated only at the surface of the films where F8BT precipitates quickly due to its lower solubility in xylene compared to Host 1. This result is similar to the studies of Krausch et al. [23] and Geoghegan et al. [24] who reported that the film surface is enriched with the component of lower surface energy.

Due to a resolution limit of the optical microscope having resolution of 5000 times, AFM measurements were carried out to observe phase separation at a higher resolution. Fig. 5(a) and (b) are topographical images of the films prepared from solution 1 by spin coating at a spin speed of 800 rpm for slow evaporation and at 1500 rpm for fast evaporation, respectively, in which very small F8BT-rich domains (bright area) disperse in a continuous phase (dark area) are seen, in agreement with the optical microscopic results. The AFM images show a slightly smoother surface for the film prepared without GYRSET. The calculated RMS roughness of the film prepared with GYRSET is 0.70 nm, whereas it is 0.60 nm for the film prepared without GYRSET. This confirms
that less degree of phase separation occurs when the solvent evaporation increases.

5. Microstructure of LEP Films prepared by dip coating process

Fig. 6 is a plot of the phase separation and film thickness as functions of withdrawal speed at different solvent evaporation rates. For ambient drying, the F8BT-rich phase ratio increases with the withdrawal speed, similar to the relationship between film thickness and withdrawal speed. The F8BT-rich ratio notably increases when the withdrawal speed increases from 0.1 to 0.3 mm/s and becomes relatively constant at higher speeds. In contrast, the higher withdrawal speed results in the lower degree of phase separation for hot-air drying. This is because at higher speed, the onset of drying occurs more rapidly. It was also found that the phase separation increases with an increase in solution concentration and polymer molecular weight, similar to the results obtained from the spin coating process.

The results obtained from AFM measurements confirm the significant effects of solvent evaporation rates. Fig. 7(a) and (b) show the topographic images of the films prepared from solution 2 by the dip coating process at the withdrawal speed of 0.1 mm/s with ambient and hot-air drying, respectively. The RMS roughness of the film prepared with ambient drying is 2.54 nm whereas it is 0.66 nm for the hot-air drying.

6. Device characterisation

6.1. Optical characteristics

The optical characterisation involved photoluminescence (PL) spectra and refractive index measurement. The PL spectra were collected using an Oriel charge coupled device (CCD) matrix spectrograph. The film was excited by a laser with the wavelength of 325 nm. The PL efficiency was calculated by a comparison between the absorbed number of photons with the emitted number of photons using an integrating sphere which is purged with nitrogen to avoid photooxidation. Further details of the PL quantum efficiency measurement can be found in Greenham et al. [25] and de Mello et al. [26].

The refractive index of the film was measured using a J. A. Woollam M-2000™ diode-array rotating-compensator.

<table>
<thead>
<tr>
<th>Fabrication process</th>
<th>Avg. PL efficiency</th>
<th>PL efficiency S.D.</th>
<th>Avg. refractive index</th>
<th>Refractive index S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin coating (w/o GYRSET)</td>
<td>55</td>
<td>2</td>
<td>1.601</td>
<td>0.001</td>
</tr>
<tr>
<td>Dip coating (ambient during)</td>
<td>52</td>
<td>3</td>
<td>1.599</td>
<td>0.007</td>
</tr>
<tr>
<td>Dip coating (hot-air drying)</td>
<td>51</td>
<td>3</td>
<td>1.600</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Table 2

PL efficiency (325 nm) and refractive index (632 nm) of films prepared by different techniques.
ellipsometer with a xenon lamp source. Ellipsometry is a technique that measures the change of polarisation of light as a function of incident angle and wavelength. The ratio of reflection coefficients for $p$-(in the plane of incidence) and $s$- (perpendicular to the plane of incidence) polarised light were recorded. Together with incidence transmission measurements, a non-linear regression analysis was performed by the WVASE 32 software to determine the refractive index. More details of the ellipsometric determination can be found in Woollam et al. [27] and Ramsdale and Greenham [28].

The measured PL efficiency and refractive indices are summarised in Table 2. The films prepared by the dip coating with the two drying methods show similar PL efficiencies (51–52%) which is slightly less than that of the film prepared by spin coating process (55%). The refractive indices at 632 nm of the three films have similar value of around 1.6. Therefore, it can be concluded that the optical properties of the films prepared by spin and dip coating techniques are generally very similar.

6.2. The Commission Internationale de l’Eclairage Chromaticity

Electroluminescence (EL) spectra were measured using an Ocean Optics spectrometer and similarly to the PL spectra, the films prepared by the spin and dip coating processes have similar EL spectra. The Commission Internationale de l’Eclairage Chromaticity (CIE) co-ordinates of the devices are relatively similar with $x$ ranging from 0.38 to 0.43 and $y$ ranging from 0.55 to 0.59 as shown in Fig. 8. The slight differences of

Fig. 8. (a) CIE chromaticity diagram and (b) insert of Fig. 8(a).
the results are probably due to the differences in film microstructure. The chromaticity diagram shows that the green light emitted from these devices lies outside the PAL (Phase Alternate Line) television colour region. Nevertheless, this does not forbid its use in Red Green Blue (RGB) displays.


The current–voltage (I–V) characteristics were measured using a Keithley 2000 Digital Multimeter and a Keithley 2400 Digital SourceMeter®, which were controlled by a Keithley 7001 Channel Switch System. The luminance (L) was simultaneously determined by a calibrated photodiode. The forward I–V curve (Fig. 9(a)) shows two regimes: (i) a low current regime with a weaker voltage dependency \( V < 2.5 \) V and (ii) a high current regime with an exponential increase of the current with voltage \( V > 2.5 \) V. The forward bias low current regime is referred to as a ‘leakage’ [3]. Light emission is observed only in the high current regime (Fig. 9(b)) where the voltage at the brightness of 0.1 cd/m² is called ‘turn-on voltage’. Both the current density and brightness increase significantly with a slight increase in the voltage from 2.5 to 3.5 V. In this range, the luminous efficiency and EL efficiency also increase (Fig. 9(c) and (d)). At the voltage beyond 3.5 V, the increase rates of the current density and luminance gradually decrease with the voltage rise and hence, the luminous efficiency and EL efficiency decline. The observation that the luminous efficiency (related to the power efficiency) decreases at a faster rate than the EL efficiency (related to the quantum efficiency) indicates the device degradation by a deterioration of the transport properties of the diode rather than by a deterioration of the optical properties of the emissive layer [4].

The luminance reaches 100 cd/m² (equivalent to Cathode Ray Tube (CRT) and most applications) at a voltage of around 3.5 V and at a current density of 2.0 mA/cm², indicating a low power consumption compared to other display technologies. The luminance as high as 5000 cd/m² can be obtained with the driving voltage of only 6 V. In addition, the device can sustain the high current density of 100 mA/cm². The maximum luminous efficiency of 6–8 lm/W and the maximum EL efficiency of 8–10 cd/A obtained at 3.5–4 V are considerably higher than those of CRT (1 lm/W) and Active Matrix Liquid Crystal Display (1–3 lm/W). The efficiency of green-emitting PLEDs has been reported to be as high as 21 lm/W, which is comparable to that of incandescent lamps [29].

The I–V–L characteristics of the devices prepared by spin and dip coating processes are comparable. The turn-on voltage is about the same for all devices (see Table 3). EL efficiencies of the spin-coated devices are consistently higher than those of the dip-coated devices as the current density of the spin-coated devices is always lower.

6.4. Lifetime characteristics

The lifetime measurement was performed by applying a constant dc current density to obtain an initial luminance of approximately 400 cd/m² and monitoring luminance, EL efficiency, and voltage until the luminance decreased by half (50% luminance). The condition of the end of device life at 50%
drop in light output is common for light emitting diodes. In order to shorten the studying time, the lifetime test was accelerated by carrying out in an oven at an elevated temperature of 80 °C.

Fig. 10(a) shows that a driving current of around 4.5–7.5 mA/cm² was required to obtain an initial luminance of 400 cd/m². As the device operated, the emission brightness (Fig. 10(b)) and the luminous efficiency (Fig. 10(c)) decreased; however, the driving voltage necessary to maintain a constant current increased (Fig. 10(d)). There is a ‘settling period’ which is the initial period that the voltage increase rapidly in a short time (around 10 h after the beginning of the test) and after which the voltage increases approximately linearly with time. Parker et al. [30] suggested that the ‘settling period’ is a result of an instantaneous morphological change of the emissive LEP layer during which the loss in luminance also occurs at a very fast rate. After the settling period, the voltage increases linearly while the luminance gradually decreases with elapsed time.

The linear voltage increase rates at different testing temperatures can be used for extrapolation of the device lifetime at room temperature [30]. At the elevated temperature of 80 °C, the voltage increases at around 80 times faster than the increase rate at room temperature. As a result, the lifetime of these devices can be roughly extrapolated to 1000–40,000 h when operating at room temperature at 100 cd/m². This range of lifetimes is acceptable since the operating lifetime of 10,000 h is generally satisfactory for most applications although some appliances such as a television and a computer monitor are expected to last for a longer time [31].

In comparison between devices prepared from different processes, although the dip-coated with hot-air drying devices required a higher current density, their lifetimes are the longest. In addition, the lifetime behaviour of the dip-coated with hot-air drying devices is different from that of the spin-coated and dip-coated with ambient drying devices (Fig. 10(b)). In general, luminance drops monotonically over the operating time. However, for the dip-coated with hot-air drying devices, initially the brightness decreases rapidly until a certain time after which there is a slight increase, followed by a decrease again. This behaviour and the fact that the hot air prolongs the device lifetime are reproducible in other solutions.

7. Device performance in relation to LEP film morphology

Table 3 shows a summary of the device performance in relation to the LEP film morphology. The values shown in the table are average data whereas the values in the brackets are standard deviation of the results. The degree of surface roughness of solution 1 and reference solution is similar due to relatively similar molecular weights of the polymers and concentrations. Although solution 1 contains xylene and reference solution contains toluene, the vapour pressure, which is a factor controlling solvent evaporation rate, of the two solvents is not significantly different. However, although the polymer molecular weight of solution 2 is lower than that of solution 3, the phase separation of the films produced from solution 2 is higher. This is due to a slower spin speed and a higher withdrawal speed used for solution 2 in order to obtain the same film thickness.

Overall, the characteristics of the devices prepared from the four solutions are similar. The differences in results are considered insignificant, except the lifetime data. The lifetime
of the devices prepared from solution 3 is considerably high while that of the devices prepared from solution 2 is quite low. The differences in the performance between devices prepared from different solutions are possibly due to different polymer chain lengths as well as different film microstructures.

Fig. 11(a) and (b) show a plot of, respectively, device efficiency and lifetime as a function of LEP film roughness. Results from the four solutions show a similar trend that for each solution, the device efficiency depreciates while the lifetime increases with a decrease in film roughness (phase separation). The results of EL characteristics agree with those presented by Cina in which an increase in luminous efficiency was found with a large-scale phase separation. This suggests that lifetime-efficiency correlation is partial and only valid for certain cases. Similar conclusion is reported by Kim et al. [4]. An optimum device performance (high efficiency and long lifetime) might be achieved with an optimum film roughness (phase separation).

8. Conclusion

This paper has shown that both process conditions and solution properties of the spin and dip coating processes affect the film morphology in a similar way. As solvent evaporation rate increases, phase separation reduces to a fine-scale. This is because fast evaporation decreases the solvent quench time and freezes the film into a non-equilibrium phase separation morphology. In terms of process condition, the rate of solvent evaporation can be controlled by spin speed and the use of GYRSET for the spin coating process, and withdrawal speed and the use of hot-air drying for the dip coating process. The solution properties also have an effect on the film morphology. Phase separation increases with an increase in polymer concentration and polymer molecular weight because both effects increase the drive for demixing.

The work has established that a high efficiency PLED can be achieved by using a blend of electron transporting emitter (F8BT) and a hole transporting polymer (Host 1). The device prepared from the blend shows a low turn-on voltage, a large current density, a high efficiency, and an acceptable lifetime. The correlation between the LEP film morphology and device performance has been investigated for the film prepared by various process conditions and solution properties. The key result shows that LEP film morphology is important in determining the device performance. The dip coating technique with hot-air drying reduces the degree of phase separation and the device efficiency; however, it extends the lifetime of the devices, especially for the devices prepared from high molecular weight polymers. As a result, in order to obtain an optimum device performance of a blend system, it is clear that the film morphology must be closely monitored and controlled.

This paper also shows that the dip coating technique shows potential as a coating technique to produce a uniform thin LEP film and similar optical and electrical properties for PLEDs.

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