Use of the $\beta$-Phase of Poly(9,9-dioctylfluorene) as a Probe into the Interfacial Interplay for the Mixed Bilayer Films Formed by Sequential Spin-Coating

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Spin-coating one polymer solution on another spin-cast polymer film is believed to result in unfavorable interfacial mixing. Here, we show some results to demonstrate that some interesting properties will be obtained in such mixed bilayer films formed by sequential spin-coating. Poly(9-vinylcarbazole) and poly(9,9-dioctylfluorene-2,7-diyl) were chosen as the first and second polymer layers, respectively. By varying the initial thickness of the first layer, some interesting variations were observed. The spectroscopic features of $\beta$-phase polyfluorene were utilized to reflect the variations at the complicated interface. Morphologies were also presented to illustrate that the variations of spectroscopic features were accompanied with some interesting morphological changes. On the basis of these results, a schematic model was proposed to gain insight into the mixed interface formed by sequential spin-coating. Polymer light-emitting devices based on such films were also investigated.

Introduction

Spin-coating is one of the most popular solution-processable techniques for fabricating ultrathin polymer films. It is widely used in the field of plastic electronics, such as polymer light-emitting diodes (PLEDs). Presently, the active layer in the conventional PLEDs is constructed of a single spin-cast polymer layer, and researchers are always trying to fabricate multilayer devices by spin-coating so that some dramatic results could be achieved. However, it is generally believed that spin-coating the second solution on the deposited film may result in the redissolving of the previous layer; this will lead to uncontrollable interfacial mixing or confusion. Researchers have developed several methods to solve this interfacial problem. For example, cross-linkable groups can be introduced into the first polymer so that the first layer can be converted into an insoluble film after thermal or UV treatments. Some research groups have also utilized the different solubility of two polymers to fabricate multilayer films with clear interfaces.

Although these methods can solve the interfacial confusion in bilayer films, some researchers still show great interest in the bilayer films with interfacial mixing. It should be noted that such a film is not the exact "bilayer" due to the complicated interfacial mixing, and it might be different from the conventional binary blend film of two immiscible polymers; thus, such films are called "mixed bilayer films" in this work. Enhanced performance was often achieved for the PLEDs based on such films; however, the interplay of the two polymer chains at the mixed interface is not very clear due to the interfacial complexity.

In this work, a simple but effective method is demonstrated to investigate the interfacial interplay of such mixed bilayer films. Poly(9-vinylcarbazole) (PVK) and poly(9,9-dioctylfluorene-2,7-diyl) (PFO) were chosen as the first and second layers, respectively. Mixed bilayer films were prepared by a sequential spin-coating process. By varying the initial thickness of the first layer, some interesting changes were observed in these films. The typical spectroscopic features of the $\beta$-phase in PFO were utilized as an effective probe to detect the complicated interfacial interplay. Film morphologies were also presented to show that the varied spectroscopic features are accompanied with some morphological changes. Furthermore, the binary blend films that consisted of PVK and PFO were also simply studied, and the results demonstrate that the mixed bilayer films possess significant differences in comparison with the binary blend films. In order to gain insight into the mixed interface, a schematic model is proposed to reasonably explain the observed variations and differences. The PLEDs were also fabricated based on these mixed bilayer films, and blue emissions were obtained with enhanced performances under optimized conditions.

Experimental Section

Materials. The anhydrous solvents used for film fabrications were purchased from Aldrich or Acros. Poly(9,9-dioctylfluorene-2,7-diyl) was prepared by a Suzuki polymerization reaction and was carefully purified in our lab. Its number mean molecular weight ($M_n$) is 15 000 with a PDI of 1.5. PVK ($M_n = 1 100 000$) was purchased from Aldrich.
Preparation of Mixed Bilayer Films. The films for optical and morphological studies were all prepared and performed on the glass substrates. Glass substrates were purchased commercially and cleaned with acetone, detergent, distilled water, and 2-propanol, subsequently in an ultrasonic bath. PVK was spin-coated on the cleaned glass substrate as the first layer from its chlorobenzene solution. The thickness of PVK was controlled by varying the solution concentrations. The deposited PVK films were put in the vacuum to remove the residual solvent. Film thickness was measured by a Tencor Alphastep surface profilometer accompanied with the measurement of film absorption intensities. Then, PFO was spin-coated on the deposited PVK layer from its toluene solution with a fixed concentration of 10 g L\(^{-1}\). The spinning rate for the PFO solution is fixed at 1300 rpm in this work. Toluene is also a solvent for the PVK sample; thus, the PFO solution will redissolve the deposited PVK layer to some extent, resulting in mixed bilayer films. The resulting films were then put in the vacuum to further remove the solvent. All the solutions and films were prepared within a glovebox under a nitrogen atmosphere.

Preparation of Binary Blends and Their Films. Binary blends of PVK and PFO were also prepared in comparison with the mixed bilayer films. They were made by physically mixing appropriate volumes of their solution. A series of mixtures were prepared with varied blending ratios. Binary blend films were then prepared through the common spin-coating process and were put in the vacuum to remove the residual solvent. The thickness of blend films was around 60 nm.

Absorption and Photoluminescence Spectroscopy. UV–vis absorption spectra were recorded on a HP 8453 spectrophotometer. PL spectra of the copolymer solution were obtained on a Fluorolog-3 spectrometer (Jobin-Yvon) using 90° angle detection.

Morphology. Because the morphological properties of binary immiscible polymer blends have been extensively studied in the literature, the morphology of the binary blend films in this work was simply studied by a Nikon Eclipse E600 POL microscope using transmitted mode. For the mixed bilayer films, the morphology was studied not only with a microscope but also by atomic force microscopy (AFM). The AFM pictures were recorded on a SPM-9500 J3 of Shimadzu using the standard tapping mode.

Fabrication and Characterization of PLEDs. PLEDs based on the mixed bilayer films were fabricated according to literature. Pre-patterned indium tin oxide (ITO) with sheet resistance 10–20 Ω/□ on a glass substrate was used as the anode. The substrate was ultrasonically cleaned with acetone, detergent, deionized water, and 2-propanol. An oxygen plasma treatment was made for 4 min as the final step just before film coating. Onto the ITO glass was spin-coated a layer of polyethyleneoxythiophene–polystyrene sulfonic acid (PEDOT:PSS) film with a thickness of 40 nm from its aqueous dispersion. The PEDOT:PSS film was dried at 80 °C for 3 h in the vacuum oven. The mixed bilayer films were then fabricated on the PEDOT:PSS layer with a process similar to those for optical and morphological studies. Then a thin layer of barium on the PEDOT:PSS layer with a process similar to those for optical and morphological studies. Then a thin layer of barium as an electron injection cathode and the subsequent 130 nm thick aluminum protection layers were thermally deposited by vacuum evaporation through a mask at a base pressure below 3 × 10\(^{-4}\) Pa. The cathode area defines the active area of the device. The typical active area of the devices in this study is 0.15 cm\(^2\). The EL layer spin-coating process and the device performance tests were carried out within a glovebox under a nitrogen atmosphere.

Current–voltage (I–V) characteristics were recorded with a Keithley 236 source meter. EL spectra and luminescence were measured by a PR 705 photometer (Photo Research). The external quantum efficiencies were determined by a Si photodiode with calibration in an integrating sphere (IS080, Laboratory).

Results and Discussion

The Principle of the β-Phase in PFO. In this work, the spectral features of the β-phase in PFO are basic tools with which to investigate the complicated interface; thus, it is necessary to give a short review on the β-phase of PFO. Compared with the disordered amorphous phase of PFO, the β-phase is the extended conformation of PFO chains and possesses lower energy. It can be described as a “planar zigzag” or a \(2_1\) helix structure. Lupton et al. have utilized single-molecule spectroscopy to demonstrate that the β-phase features of PFO are the results of stress-induced backbone planarization of single polymer chains. Formation of β-phase chains in the PFO films can be affected by many experimental treatments, for example, thermal annealing, relaxing the PFO chains by organic solvent vapor, thermodynamic or mechanical stress of polymer chains, chemical modifications of PFO chains, thickness variations of PFO films, and so on. It was noted from these reports that molecular weight and polydispersity (PDI) of PFO can also affect the appearance of β-phase chains in the as-cast PFO film.

The β-phase chains in PFO can be easily identified by the UV–vis absorption and photoluminescent (PL) spectra. Figure 1a presents the spectroscopic properties of PFO containing β-phase chains. The spectroscopic properties of amorphous PFO are also displayed in Figure 1 for comparison. It can be observed that a β-phase PFO film possesses the typical shoulder absorption around 431 nm in comparison with the amorphous PFO film. Such shoulder absorption is the most important feature of β-phase PFO. It can also be observed that PL spectra of the two samples show distinct differences. A PFO film containing β-phase chains possesses a well-defined vibronic PL spectrum, peaking at 434 nm; however, the amorphous PFO film possesses a different vibronic structure in the PL spectrum, peaking at 424 nm.

In a word, only the conformational variations can determine the appearance of β-phase chains in ultrathin PFO films, and
the slight conformational change will entirely transform the photophysics of the system, resulting in the corresponding spectroscopic variations. That is to say, such spectroscopic variations in the film state are very sensitive to the chain conformation. Thus, the \( \beta \)-phase chains in PFO films can be utilized as a probe to detect the conformational variations, and these provide access to the complicated interfacial interaction in the PVK/PFO mixed bilayer films. Figure 1b also presents the normalized absorption and PL spectra of the neat PVK film. In addition, it should be mentioned that the as-cast neat PFO film in this work possesses significant \( \beta \)-phase features.

**Washing PVK Film by Pure Toluene.** The main topic in this article focuses on the mixed bilayer films fabricated by a sequential spin-coating process; thus, in order to know what will happen to the deposited PVK layer during a second spin-coating, pure toluene is first used in the second spin-coating process. In the experiment, toluene was dripped onto the deposited PVK film, followed by spinning at 1300 rpm. Such a process can be called “washing”. Table 1 presents the thickness changes of PVK films before and after this washing process. It is obvious that, when the initial thickness of the PVK film was 100 or 200 Å, the PVK film was entirely washed off from the substrate and the residual PVK was undetectable. However, for the initial thickness of 400 Å and above, residual PVK layers could clearly be detected. These results indicate that the second spin-coating can redissolve the deposited PVK films; for the thinner films almost all the PVK on the substrate will be redissolved into the toluene and washed off, and for the thicker films partial PVK will be redissolved and a residual film will be left on the substrate after the washing process. The results also imply that the initial thickness of deposited PVK films plays an important role during the second spin-coating process.

**Properties of the Binary Blend Films.** As demonstrated above, the second spin-coating process will redissolve the deposited PVK film into the second solvent. This means that, if the pure toluene is replaced by the PFO solution, a physical binary mixture containing PFO and PVK might be obtained during the second spin-coating, resulting in a binary blend film on the substrate. Thus, it is very necessary to show some properties of the binary blend films, so that clearer discussions and comparisons could be given in the following sections. It should also be mentioned that PVK and PFO are immiscible polymers.9,12

In the experiment, PVK was mixed with PFO in toluene at varied ratios, and a series of binary blend films were fabricated based on these mixtures. Figure 2 presents the absorption and PL spectra for these binary blend films. It can be observed that the \( \beta \)-phase features of PFO in the blend films were not affected by the blend ratios. Microscopic images were also obtained for these blend films as shown in Figure 2. It is obvious that distinct lateral phase separation will be induced by increasing the blend ratio. Similar observations have been reported in the literature.9

### Table 1: Thickness of PVK Films before and after the Washing Process Using Toluene Solvent

<table>
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<tr>
<th>initial thickness before washing (Å)</th>
<th>approximate thickness after washing (Å)</th>
</tr>
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<tbody>
<tr>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>200</td>
<td>4</td>
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<td>400</td>
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<td>900</td>
<td>80</td>
</tr>
<tr>
<td>1100</td>
<td>130</td>
</tr>
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</table>

*Film thickness was measured by a Tencor Alphastep surface profilometer accompanied with the measurement of film absorption intensities. (See Supporting Information.)*

All these results show that blending PVK into the PFO matrix can affect the film uniformity; however, the \( \beta \)-phase features in PFO cannot be affected due to the phase separation. In other words, the \( \beta \)-phase chains still exist in the PFO-rich phases in the binary blend films, and the chain conformation cannot be affected by physical blending.

In addition, it is notable that the shoulder absorption of \( \beta \)-phase at 431 nm seemed to disappear when the blend ratio reached 50:100; however, this does not mean the disappearance of the \( \beta \)-phase chains. In fact, at higher blend ratios, the distinct phase separation will reduce the transparency of the blend films due to the light diffusion arising from those sea-island-like domains; this will affect the detection of \( \beta \)-phase absorption in the absorption measurements. In this case, the \( \beta \)-phase chains in the film can be detected by the corresponding PL spectra, which clearly show \( \beta \)-phase emissions.

**Spectroscopic Properties of the Mixed Bilayer Films.** In this section, properties of the mixed bilayer films will be discussed. In the experiment, the PFO solution was spin-coated on the deposited PVK films. The initial thickness of PVK films varied from 0 to 900 Å, and a series of mixed bilayer films were obtained. Figure 3, parts A and B, shows the absorption and PL spectra of these films, respectively. From the absorption spectra, it can be clearly observed that the shoulder absorption at 431 nm is significantly reduced with an increase of the initial thickness of PVK layers. It even disappears entirely when the
Thickness of the PVK layer exceeds 400 Å. Together with these changes in absorption spectra, PL spectra of such films also show distinct dependence on the initial thickness of PVK layers (Figure 3B). When the thickness of the PVK layer is 0, 100, and 200 Å, the shapes of emission spectra display slight changes; however, when the thickness exceeds 400 Å, the PL peak around 421 nm shows significant enhancement. All these variations imply that the appearance of $\beta$-phase chains can be affected during the second spin-coating process, indicating the transformation of molecular conformation; in other words, the conformation of PFO chains not only is affected by the PVK surface layer during the second spin-coating process, but also has crucial correlations with its initial thickness.

It is believed that the second spin-coating will redissolve the deposited polymer resulting in a binary mixture, and this might lead to a binary blend film on the substrate; however, in the case of this work, the fact is not as simple as believed. By comparing the spectral results in Figure 2 with those in Figure 3, it can be noted that the $\beta$-phase features are significantly affected by the redissolving process on the PVK film, but they are not affected by the physical blending with PVK. This implies that the “redissolving” and “mixing” processes on the deposited PVK films are distinctly different from the physical blending of two components; that is, the deposited PVK films can affect the molecular conformation of PFO chains during the second spin-coating, resulting in the disappearance of $\beta$-phase features.

Such influence shows significant dependence on the initial thickness of PVK layers. Thus, it can be concluded that the PVK layer on the substrate plays a dramatic role during the second spin-coating process and brings some interesting results to the mixed bilayer films.

**Morphology of the Mixed Bilayer Films.** Together with these spectroscopic changes, the film morphologies also display corresponding variations in the mixed bilayer films. Figure 3C shows the microscopic images of these films, and varied morphologies can be distinctly observed. Figure 3C, images C-2 and C-3, displays well-defined sea-island-like structures, which are similar to those in the binary blend films and can be treated as the lateral phase separation (Figure 2); however, Figure 3C, images C-1, C-4, and C-5, shows continuous films. These results indicate that morphological alterations in the mixed bilayer films also show a significant correlation with the thickness of the PVK layer.

Besides these microscopic pictures, atomic force microscopy (AFM) images were also taken for Figure 3C, images C-2 and C-4. Figure 4 displays the AFM topographical images of these films. The initial thicknesses of PVK layers in these films are 100 and 400 Å, respectively. Sectional views along the line indicated by the arrows in the height images are also displayed in Figure 4. It is obvious that, when the PVK layer was 100 Å, the significant holes represent the micrometer-scale lateral phase separation formed in the film. In contrast, when the PVK layer

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**Figure 3.** Absorption spectra (A), PL spectra (B), microscopy images (C), and EL spectra (D) of the mixed bilayer films with varied PVK thickness. The dashed lines in columns (A), (B), and (D) represent the wavelengths of 431 nm, 434 nm, and 434 nm, respectively. The PL spectra were obtained by exciting the film with a laser of 375 nm from the PFO side. The EL spectra were obtained from the newly fabricated devices under 2 mA.
were that both the lateral phase separation and the deposited PVK layer. Among all these facts, the most important neous films. All these facts imply the crucial roles of the thickness of the PVK layer, film morphologies can be switched morphologies of the mixed bilayer films. By changing the initial process, resulting in the disappearance of \( \beta \)-phase features; such influences could not be obtained by physically blending PVK into PFO matrixes. (iv) The deposited PVK will affect the morphologies of the mixed bilayer films. By changing the initial thickness of the PVK layer, film morphologies can be switched between the micrometer-scale phase separation and homoge neous films. All these facts imply the crucial roles of the deposited PVK layer. Among all these facts, the most important are that both the lateral phase separation and the \( \beta \)-phase features display distinct correlations with the initial thickness of deposited PVK films. Thus, in order to gain insight into the sequential spin-coating process of this work, it is very necessary to give a reasonable explanation for both of the phenomena.

Phase separation of immiscible polymers is an old but interesting topic in polymer physics.\(^{14}\) Kajiyama et al. had proposed a lateral spreading mechanism to explain the height variation of the phase-separated morphology in the binary blend films after spin-coating.\(^{14a}\) Steiner et al. had obtained three-dimensional information on the domain morphology in the thin films by using AFM combined with selective dissolution; some details and mechanisms about the phase separation had been studied.\(^{14b}\) Heriot et al. have provided evidence that a blend of two polymers will first undergo vertical stratification during the spin-coating process, followed by the lateral phase separation.\(^{14k}\) Friend et al. have disclosed that the lateral and vertical separation will both exist in the binary phase-separated films.\(^{14d,e,i,o}\) It is also known that surface energy often plays a very important role during the spin-coating process.\(^{14b,e}\) For example, Steiner et al. reported that when a binary polymer mixture is spin-coated on the patterned or modified surface, homogeneous films can be obtained with suppressed lateral phase separation. Such a homogeneous film is believed to possess a vertical stratification with a clear interface, and this bilayer structure is often treated as the vertical phase separation of two polymers.\(^{14d,e}\)

On the basis of Steiner’s model,\(^{14b}\) the disappeared lateral phase separation in the mixed bilayer films of this work might be explained as follows. During the second spin-coating, the redissolved PVK will form a binary mixture with PFO; the residual PVK film on the substrate can act as a surface layer which might change the surface energy for the second spin-coating. Thus, after the second spin-coating process, homogeneous films can be obtained. On the basis of this model, it can also be concluded that distinct vertical phase separation has to exist in the films. However, this conclusion could not reasonably explain the disappearance of \( \beta \)-phase features. Because the vertical phase separation is attributed to the polymer demixing and will result in the PFO-rich domains, such a polymer demixing process could not transform the conformation of PFO chains according to Figure 2. Thus, such a vertical phase separation model cannot give a reasonable explanation for the disappeared \( \beta \)-phase features shown in Figure 3.

To give a reasonable explanation for the disappeared \( \beta \)-phase features, some important reports should be mentioned here. Kajiyama et al. had proposed a lateral spreading mechanism to explain the height variation of the lateral phase-separated morphology in the binary blend films after spin-coating.\(^{14a}\) Huang et al. have used the tensile deformation technique to prepare the oriented blending film containing PFO and poly-ethylene (PE).\(^{11m}\) In Huang’s experiments, the PFO was blended into the PE matrix and a blend film was cast. They found that, by drawing the film at different drawing ratios, the \( \beta \)-phase features of PFO in PE matrixes can be modulated and even
disappear at the high drawing ratios. These results showed that the PFO chains in the films vary from the initial phase-separated state to the final molecular dispersion in the PE matrix by increasing drawing ratio.

On the basis of Kajiyama’s spreading mechanism\textsuperscript{14a}, Steiner’s model\textsuperscript{14b} and Huang’s model\textsuperscript{11m} a schematic process is now proposed in Figure 5 to explain the thickness-dependent phenomena observed in this work. First, a PVK film was formed on the glass substrate (Figure 5a). Then, the PFO in toluene was dripped onto the deposited PVK layer (Figure 5b). At the early stage of the drip-drop, PVK chains at the surface can be partially dissolved into the PFO solution. When the rotator is spinning, the solution will flow outward under centrifugal forces, and the PVK layer will be washed off along with the spreading solution. According to the washing process discussed above, if the PVK layer is not thick enough, it will be entirely washed into the PFO solution during the spinning, and the solution can be treated as a binary mixture; this will result in the binary blend films after spin-coating. Thus, the spectroscopic and morphological properties of this case possess results similar to those observed for binary blend films (Figure 2 vs Figure 3A–C). However, if the PVK layer is thick enough, it will be partially washed off and a residual PVK film will form on the substrate. For this case, since the PVK possesses a high $M_n$, part of one PVK chain can be fixed in the undissolved PVK film and the other part can be dissolved into the second solution. These surface-immobilized molecules may form a brush structure\textsuperscript{15} as illustrated in Figure 5c, which is similar to the organic monolayer on the Au substrate in the literature.\textsuperscript{14b,3} When the rotator is spinning, the free parts of those fixed PVK chains will be oriented under the centrifugal force along with the outspreading solution. After solvent evaporation, PFO chains will be homogeneously dispersed in the PVK matrix as assumed in (d).

Electroluminescent Performance of the Mixed Bilayer Films. PFO and PVK are both widely studied materials in the field of polymer light-emitting devices. To further demonstrate the electroluminescent (EL) properties of the mixed bilayer films, standard PLED devices were fabricated on the basis of Figure 5. A schematic model describing the sequential spin-coating process. (a) Deposit PVK film from its chlorobenzene solution on glass substrate. (b) Drip-drop of PFO solution on deposited PVK film; (c) Spin-coating the PFO solution on the PVK layer. The PVK layer is first redissolved into the PFO solution partially and forms a brush structure as assumed in the inset. With the centrifugal force of spinning, free parts of PVK chains will be oriented along with the outspreading solution. After solvent evaporation, PFO chains will be homogeneously dispersed in the PVK matrix as assumed in (d).

Figure 5.

Figure 6. Current density–voltage (a), brightness–voltage (b), and EQE–current density (c) characteristics of the PLEDs based on the mixed bilayer films.
such films. The device configuration is ITO/PEDOT:PSS (40 nm)/mixed bilayer films/Ba(4 nm)/Al(130 nm). Figure 3D shows the initial EL spectra of devices with varied PVK thickness. It is obvious that the EL spectra also display a dependence on the PVK thickness similar to those for PL and absorption spectra. It is known that the \( \beta \)-phase of PFO possesses lower energy than the amorphous phase; thus, \( \beta \)-phase units might act as the energy-trapping sites in the PFO films through efficient energy transfer.\(^{7c}\) This implies that, when the charged carriers inject into the PFO films, they will tend to be captured by the \( \beta \)-phase sites rather than by the amorphous sites, even when the amount of \( \beta \)-phase units is low. Thus, by comparing images D4 and D5 with D1–3 in Figure 3, it can be concluded that the thicker PVK layers can significantly suppress the \( \beta \)-phase chains in the mixed bilayer films. These EL spectra can further confirm the schematic model proposed in Figure 5. In addition, the green emission around 520 nm was not observed in these initial EL spectra.

Figure 6 shows the current density–voltage, brightness–voltage, and external quantum efficiency–current density characteristics of these devices. Table 2 also summarizes their performances. By increasing the initial thickness of the PVK layer, the turn-on voltages of the devices show a significant increase due to the increased total thickness. Among these devices, the best performances are achieved when the initial EL performances are still under consideration.

### Conclusion

This work has demonstrated the properties of the mixed bilayer films fabricated by a sequential spin-coating process. PVK and PFO were chosen as the first and second polymer layers, respectively. By changing the initial thickness of the first layer, varied features were observed for such mixed bilayer films. The typical spectroscopic features of the \( \beta \)-phase in PFO were utilized as a probe to detect the complicated interfacial variations. Film morphologies were also presented to show that the spectroscopic variations were accompanied with some morphological changes. Furthermore, the binary blend films consisting of PVK and PFO were also simply studied, and results demonstrate that the mixed bilayer films possess some different features in comparison with the binary blend films. In order to gain insight into the mixed interface, a schematic model was assumed to explain the observed variation and differences. The PLEDs were also fabricated on the basis of these mixed bilayer films, and blue emission was obtained with enhanced performance when the initial thickness of the PVK layer is optimized.

### Acknowledgment

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### Supporting Information Available:

The details of measuring the thickness of PVK films is available free of charge via the Internet at http://pubs.acs.org.

### References and Notes


### Table 2: EL Performances of the PLED Based on the Mixed Bilayer Films

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<tr>
<th>initial thickness of PVK layer (Å)</th>
<th>turn-on voltage (V)</th>
<th>( L_{\text{max}} ) (cd m(^{-2}))</th>
<th>( LE_{\text{max}} ) (cd Å(^{-1}))</th>
<th>( QE_{\text{max}} ) (%)</th>
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<td>3035</td>
<td>1.06</td>
<td>0.99</td>
<td>(0.16, 0.09)</td>
</tr>
<tr>
<td>100</td>
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<td>4064</td>
<td>1.15</td>
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<td>200</td>
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<td>1.46</td>
<td>1.37</td>
<td>(0.16, 0.10)</td>
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<tr>
<td>400</td>
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<td>1.00</td>
<td>0.93</td>
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<td>3710</td>
<td>0.88</td>
<td>0.83</td>
<td>(0.17, 0.10)</td>
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(10) The method for measuring the film thickness is described in detail in the Supporting Information.
