Flexible organic light-emitting diodes with transparent carbon nanotube electrodes: problems and solutions

Liangbing Hu¹, Jianfeng Li², Jun Liu², George Grüner¹ and Tobin Marks²

¹ Department of Physics, University of California, Los Angeles, CA 90095, USA
² Department of Chemistry, Northwestern University, Evanston, IL 60208-3113, USA

E-mail: hlb@physics.ucla.edu and t-marks@northwestern.edu

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Abstract

We study in detail here the application of transparent, conductive carbon single-wall nanotube (SWNT) networks as electrodes in flexible organic light-emitting diodes (FOLEDs). Overall comparisons of these networks to the commonly used electrodes poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS) and indium tin oxide (ITO) are made, and SWNT networks are shown to have excellent optical and superior mechanical properties. The effects of protruding nanotubes, rough surface morphology, and SWNT network–adjacent layer dewetting are shown to be problematic, and approaches for addressing these issues are identified. The mechanical properties of SWNT networks and ITO are compared, and SWNT networks are shown to exhibit more durable sheet conductance under bending, which leads to bendable FOLEDs. We demonstrated FOLEDs with SWNT network anodes that exhibit outstanding light output and meet display requirements. SWNT-based FOLEDs show comparable lifetime performances to ITO-based devices. The promise and the remaining challenges for implementing SWNT networks in organic light-emitting diodes are discussed.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Flexible electronics is an emerging area with novel applications which are not possible with traditional silicon-based electronics. Recently development examples are high performance thin film transistors, printable and flexible electrodes, ultrathin flexible solar cells [1–4]. Organic light-emitting diode (OLED), particularly flexible OLED (FOLED), are rapidly approaching large-scale commercialization due to the attractions such as low cost, light-weight, high energy efficiency [5–7]. Indium tin oxide (ITO) is traditionally used in OLEDs due to its high transmittance and electrical conductivity. However, there are problems of using ITOs for OLED, especially for FOLED, such as diffusion of oxygen in charge transport/emission layers, relative low work function, corrosion susceptibility, and more importantly, poor mechanical properties [8–11]. For flexible electronics, the electrodes are shown to be one key component in full flexible electronics realization [1]. Two-dimensional mesh networks of single-walled carbon nanotubes (SWNTs) have been extensively studied and applied as optically transparent and electrically conductive electrodes for various types of optoelectronic devices such as organic solar cells, liquid crystal displays (LCDs), and touch screens [12–15]. In particular, because of their high work function and mechanical flexibility, SWNT networks are promising anode materials for flexible FOLED applications. They can provide additional functionalities compared with traditional ITO electrodes, especially in terms of superior mechanical properties. Efficient small molecule and polymer devices with SWNT network anodes have been demonstrated [16, 17]. Various methods of depositing SWNT networks on plastic substrates have been demonstrated which includes spraying coating, dip coating, filtration–PDMS
The film non-uniformity is <5% for SWNT films and <10% for PEDOT.

Table 1. Key parameters of SWNT networks, PEDOT:PSS, and ITO for FOLED device applications. Poly(9,9-diocytfluorene-co-benzothiadiazole) (BT) is used as the active layer in these FOLEDs. $R_s$ and $T$ are sheet resistance and optical transmittance, respectively. The film non-uniformity is <5% for SWNT films and <10% for PEDOT.

<table>
<thead>
<tr>
<th>Anode</th>
<th>$R_s$ (Ω/sq)</th>
<th>$T$ at 550 nm (%)</th>
<th>Work function (eV)</th>
<th>Roughness (nm)</th>
<th>Bending radius (mm)</th>
<th>Highest light output (cd cm$^{-2}$)</th>
<th>Current efficiency (cd A$^{-1}$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWNT</td>
<td>300</td>
<td>90</td>
<td>4.7–5.2</td>
<td>8–10</td>
<td>&lt;2</td>
<td>3500</td>
<td>1.6</td>
<td>[12, 13, 16]</td>
</tr>
<tr>
<td>PEDOT</td>
<td>300</td>
<td>80</td>
<td>5.0</td>
<td>1.1</td>
<td>10</td>
<td>1000</td>
<td>8.8</td>
<td>[30]</td>
</tr>
<tr>
<td>ITO</td>
<td>10–300</td>
<td>80–88</td>
<td>4.7</td>
<td>1.5</td>
<td>10</td>
<td>$5 \times 10^5$</td>
<td>15–17</td>
<td>[26, 31–33]</td>
</tr>
</tbody>
</table>

The film non-uniformity is <5% for SWNT films and <10% for PEDOT.

2. Results and discussion

2.1. Transparent anode materials for FOLEDs

SWNT networks, PEDOT:PSS, and ITO are currently used as anodes in a variety of OLED and PLED devices. In addition, graphene thin films, nanowire networks, thin metal films, and other types of transparent and conductive oxides (TCOs) are emerging as new classes of highly transparent and conductive anode materials [24–27]. Traditionally, ITO has been used as an anode; transparent electrodes composed of PEDOT:PSS have a relatively longer history than SWNT networks. While there has been progress in improving the properties of PEDOT:PSS, its poor chemical stability and electrical inhomogeneity remains a major problem. Figure 1(a) compares the optical transmittance of the three materials as films on glass in the visible wavelength range. The transmittances were measured using a Beckman Coulter DU-640 spectrophotometer and the sheet resistance is measured with a surface resistivity meter (EDTM, Inc.). The sheet resistance of ITO spans a broad range which depends on the substrate, crystallinity, and doping level. ITO transmittance spectra have a distinctive feature at ~450 nm which leads to slightly yellowish color. In contrast, SWNT networks have a flat spectrum and neutral color. This difference is more pronounced for SWNT networks having higher transmittance, and the neutral color is preferred for display applications since it eliminates the need for complicated color adjustment components. In addition, SWNT networks have a lower refractive index in the visible range ($n \sim 1.5$) than does ITO ($n \sim 2.0$). This leads to greater OLED readability in bright light backgrounds [26]. Furthermore, SWNT networks are transparent in the infrared wavelength region, while PEDOT and ITO are not [28]. Infrared transparency enables OLED device function in this wavelength range for night vision and military applications.

Table 1 lists key SWNT network, PEDOT:PSS, and ITO films on glass having comparable sheet resistance.

Figure 1. Optical transmittance characteristics in the visible range for a SWNT network, PEDOT:PSS, and ITO films on glass having comparable sheet resistance.

stamp-based transfer printing, meyer rod coating and direct chemical vapor deposition followed by transfer [18–21]. Large-scale industrial roll-to-roll manufacturing of transparent SWNT networks using solution-based processes has also been demonstrated [22]. All of these advances pave the way for the integration of transparent SWNT networks in commercial FOLEDs. However, there are several challenges yet to be surmounted before commercialization will be possible. The relatively high network sheet resistances and rough surface morphologies present two major hurdles.

Improving the material purity, chemical doping of SWNT network or using separated SWNTs for improved transparent electrodes based on SWNTs have been demonstrated by several groups [23]. However, the typical values for stable transparent electrodes based on SWNTs is 100–200 Ω/sq with 80–85% transmittance, which is lower than then high quality ITO on plastic with values of 30–50 Ω/sq and 80–85% [16]. The higher sheet resistance will lead to large voltage drop for OLEDs. The surface roughness for SWNTs is typical ~10 nm, much higher than that of ITO substrate on plastic with values of ~1 nm [16]. To our best knowledge, it is the first time that we analyze in detail and optimize sheet resistance, surface roughness, and surface modification effects in FOLED devices in this paper. We also compare the lifetime and mechanical property differences between ITO- and SWNT-based FOLED devices.
limitation for device function. However, spin-coating or self-assembling another conductive polymer layer on the network can substantially decrease the surface roughness. As shown in Table 1, a major advantage of SWNT networks is their mechanical flexibility in terms of bending. As discussed below, SWNT networks do not show significant failure after bending to curvatures of less than 2 mm, while ITO or PEDOT films show catastrophic failure when bent to 7 mm curvature. The thickness of the plastic substrates is normally in the range of 125–175 μm. The active film thickness for SWNT, ITO or PEDOT is 30–100 nm. Therefore, these electrode materials undergo the similar mechanical strain when mechanical bending test is performed. The more robust mechanical properties of SWNT films is likely due to the better mechanical properties of individual SWNTs and their strong binding between each other. Optimum achieved performance in terms of FOLED light output intensity and current efficiency are also summarized in Table 1 [29–33]. All the three anode materials enable sufficient light output intensity for display applications where 200 cd cm$^{-2}$ is typically needed [29].

As discussed below, light output uniformity and device lifetime are equally important parameters when choosing the optimum electrode material among these three FOLED anode candidates.

### 2.2. Sheet resistance effects on OLED performance

One major disadvantage of transparent SWNT mesh networks in FOLED applications is its high sheet resistance compared to ITO electrodes at a fixed optical transmittance. To evaluate sheet resistance effects on device performance, SWNT network- and ITO-based devices were fabricated. The material components and device structure are shown in Figure 2. The device fabrication details are provided in the experimental section. Note that the hole transport layer, PEDOT:PSS, is used in some devices and its effect will also be discussed.

Figure 3 shows images of operating OLEDs based on 20 Ω/sq ITO on glass and 200 Ω/sq SWNT on PET with the same device structure and active layers. Compared to the ITO–OLED, the SWNT–OLED not only exhibits lower light output intensity, but also poor light emissive uniformity. The device dimensions are 2.0 mm × 5.0 mm for the ITO-OLED and 40 mm × 10.0 mm for the SWNT-based device. This poor emissive uniformity can be explained on the basis of differences in anode electrical properties, including the high SWNT network sheet resistance. The cathode (100 nm Al, <1 Ω/sq) is highly conductive and therefore the voltage drop across the surface should be negligible. For anodes composed of SWNT networks, the applied voltage drops as the distance to the electrical contacts increases. Due to the high sheet resistance, the voltage drop along the current flow direction is more dramatic than in the ITO case. Although the light output is clearly not uniform for a SWNT-OLED with 2.5 mm × 5.0 mm dimensions, the voltage drop will decrease significantly when the device dimensions are decreased, as in reported OLED displays using SWNT anodes where pixel areas are in the range of few hundred μm—approximately 100× less than the present dimensions. Therefore, the voltage drop will be far lower and the light output uniformity appreciably increased. However, for large-area solid state lighting, the high SWNT network sheet resistance will be problematic in the absence of another approach. The engineering approach to solve this problem is to place highly conductive metal mesh on top of the SWNT network with minimal contact resistance to decrease the width of OLED device (w), where $R_s$ and device dimensions of length (l) and width (w), scale as $(lw)^2R_s$ [34–36].
dark areas can be observed in the light-emitting region of the SWNT-OLED. The small dark areas on the SWNT-OLED are possibly due to the impurities of CNT network and the porous structure of CNT network that cause the inhomogeneous light output.

Figure 4 shows details of the performance differences in terms of current density and light output intensity. In these devices, a PEDOT:PSS interfacial/planarization layer was used in both cases to improve hole injection from the anodes. Then PEDOT:PSS is used as transparent electrode in devices, ~100 nm thickness is needed. However, in our OLED devices, PEDOT:PSS of a few nanometer thick is used. PEDOT is used as a surface modification layer to enhance the charge transfer. Since its thickness is much smaller than where PEDT:PSS is used as transparent electrode and CNT network conducts the electrical current, the incorporation of PEDOT in our device will not affect the mechanical flexibility and chemical stability. Both the SWNT- and ITO-based devices produce sufficient light output for display applications where 200 cd m\(^{-2}\) is needed [29]. Up to 10 V, the current density of the ITO-based device is approximately 10 \(\times\) that of the SWNT network-based device. The current density of the latter flattens beyond ~13 V. In both cases, the light output difference increases with voltage up to ~10 V while at higher voltages, the SWNT device light output begins to decline. This response for the SWNT-based device is likely due to the porous nature of the SWNT network. Possible voids may remain even after the PEDOT layer application. Furthermore, at higher voltages, evolved heat may lead to SWNT matrix reconstruction and delamination from the electrode. This would hinder hole transport from the anode and erode the balanced hole and electron injection characteristics.

2.3. Morphology effects

SWNTs have high aspect ratios, and the 1–2 \(\mu\)m lengths are much larger than the active layer thickness for the device in figure 2. Individual SWNTs have high current-carrying capacity, and SWNT penetration of the active layer connecting the anode and cathode could easily short the devices. Note that SWNT protrusion is observed in SEM images (figure 5). These protruding tubes may result from the CNT deposition process,
and could cause catastrophic device failure. Especially for the present transparent SWNT networks on PET, fabricated by the filtration and PDMS stamping, we find that more than 80% of OLEDs based on such anodes are shorted. Separation between the PDMS and PET substrate during the transfer process can generate such protruding tubes [34]. There are several approaches to solving this problem. Instead of using the PDMS stamping procedure, other coating methods such as direct slot die coating can avoid tube detachment from the surface. Also, improving the cohesion between the nanotubes and the substrate by surface activation or ink formulation substantially suppresses protrusion [17]. For film handling during device manufacture or processing, poor nanotube–bare substrate cohesion can lead to tube release from the surface. Top coating of the SWNT network with another thin polymer layer to improve SWNT adhesion to the substrate is also effective [37].

Another challenge with respect to anode morphology is the high intrinsic surface roughness arising from SWNT dimensionality. The high aspect ratio leads to a highly porous surface morphology. While this particular surface structure is advantageous for energy storage applications such as batteries and supercapacitors [38], it is disadvantageous for optoelectronic devices such as organic solar cells, liquid crystal display (LCDs), and OLEDs where very smooth surfaces (root-mean-square (RMS) roughness <1 nm surface) are required. PEDOT and ITO are superior in this regard, and further suppression of their surface roughness requires treatments such as plasmas or annealing. However, these methods are not applicable to SWNT network films; e.g., plasmas simply etch away SWNTs. One obvious method to improve surface morphology is to fill the pores with another material. Figure 6 compares a SWNT network before and after spin-coating on a PEDOT solution to improve the surface morphology. It is evident that the surface smoothness is greatly improved by PEDOT. For comparison, the surface structure of PEDOT and ITO are shown in figure 6 as well, with the surface roughness of 1.5 nm for the ITO and 1.1 nm for the PEDOT. From figure 4, note that at high operating voltages, SWNT device performance degrades, which may reflect field concentration effects on the rough SWNT surface. Instead of a single-step
PEDOT coating and annealing process, multiple-step PEDOT coating should help deposit a smoother, void-free SWNT network for enhanced device performance.

Figure 7 summarizes the performance of devices having the structure shown in figure 2. For this particular device set, no shorting from protruding SWNTs is observed. The PEDOT coating dramatically improves the device performance. In particular, note that the turn-on voltage decreases by $\sim 8$ V, and the light output at fixed voltage increases by approximately $100 \times$. At this point, the mechanism(s) of such improvements is not unambiguous, however there are two possibilities. The effects may due to the improved surface morphology and/or to enhanced hole injection through the PEDOT layer as for ITO-based devices. The PEDOT:PSS has been optimized for intimate wetting of the adjacent layer in optoelectronic devices, while the SWNT network itself has poor wetting due to its hydrophobic nature. PEDOT:PSS coating could in principle diminish the dewetting of the active layer and also local electrical field effects due to the one-dimensional nature of SWNTs. Further improvement should be possible as anode fabrication or engineering is optimized for using SWNT anodes.

2.4. PEDOT–SWNT network wetting

The interface between SWNTs and the active layer is critical for OLED performance, including energy level matching as well as morphological/surface energetic compatibility. Due to the hydrophobic nature of the SWNT network, the physical interfacial contact between the adjacent PEDOT:PSS layer and the network is doubtless poor. There is often difficulty in spin-coating PEDOT on SWNT networks. Prior to PEDOT coating, another thin layer of material is frequently applied, such as a thin layer of parylene C or a short duration plasma treatment to make the surface more hydrophilic for better adhesion in subsequent PEDOT deposition [17, 37]. Here we find that the wetting of the SWNT network by the PEDOT suspension is increased by adding methanol to the PEDOT suspension. The optimized volume ratio between PEDOT:PSS (Baytron P) and MeOH used here is 1:2, with all annealing conditions the same. Figure 8 shows AFM images of SWNT surfaces after PEDOT spin-coating. Note that addition of MeOH in PEDOT–PSS suspension decreases the surface tension of PEDOT–PSS, which leads to a far smoother surface morphology of film. The surface roughness is 4 nm in figure 8(a) and is 0.95 nm in (b).
The above decrease in anode surface roughness leads to significantly enhanced OLED device performance (figure 9). The light output of PEDOT–PSS:MeOH device is less than the PEDOT–PSS device below 8 V, but is clearly greater above 8 V. More importantly, there is no decline in light output at higher voltages for PEDOT–PSS:MeOH modified device. In contrast, the light output decreases sharply at high voltage in PEDOT–PSS case. This difference indicates that surface roughness is critical for stable device operation, especially in high voltage range. Furthermore, the PEDOT–PSS:MeOH modified device exhibits much greater current efficiency at high voltages. The PEDOT–PSS and MeOH mixing ratio has not been optimized. Based on this study, we suggest that there room to improve device performance by further enhancing the wetting between the SWNT network and the adjacent layer. Table 2 summarizes key OLED performance parameters for devices using PEDOT–PSS and PEDOT–PSS:MeOH-coated SWNT network anodes. Furthermore, the incorporation of a thin layer of PEDOT on top of SWNT network would modify the work function and the charge injection from the active layer. Further characterization of work function change for SWNT network after PEDOT coating is needed to further understand the device performance.

2.5. Lifetime comparison of ITO- and SWNT-based OLEDs

We also compare the lifetimes of SWNT network- and ITO-based unencapsulated OLEDs. The test was carried out at a constant light output intensity of 1200 cd m$^{-2}$ initial luminance for the SWNT network-based anode (figure 10). The current density is 0.12 and 0.05 A cm$^{-2}$ for SWNT network- and ITO-based OLEDs. The light output in the first hour decreases precipitously for both ITO and SWNT network-based OLED devices. For comparison, the lifetime is found to be 52 h for an initial light intensity of 1400 cd m$^{-2}$. The lifetime test results with the similar initial light intensity are similar for OLEDs based on SWNT networks and ITO anodes.

Table 2. Summary of SWNT network anode and device performance for different anode surface treatments.

<table>
<thead>
<tr>
<th></th>
<th>Without PEDOT:PSS</th>
<th>With PEDOT:PSS</th>
<th>With PEDOT:PSS–MeOH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turn-on voltage (V)</td>
<td>12</td>
<td>4</td>
<td>4.7</td>
</tr>
<tr>
<td>Maximum light output (cd m$^{-2}$)</td>
<td>10</td>
<td>490</td>
<td>1000</td>
</tr>
<tr>
<td>Maximum current efficiency (cd A$^{-1}$)</td>
<td>Very low, &lt;0.1</td>
<td>0.5</td>
<td>0.85</td>
</tr>
<tr>
<td>Surface roughness (nm)</td>
<td>8–10</td>
<td>4</td>
<td>0.95</td>
</tr>
<tr>
<td>Planarization</td>
<td>No</td>
<td>Yes</td>
<td>Best</td>
</tr>
</tbody>
</table>

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Figure 9. OLED device performance for SWNT network anodes after PEDOT–PSS coating with and without mixing with MeOH: (a) current density versus operating voltage; (b) light output versus voltage; (c) current efficiency versus voltage. Mixing with PEDOT–PSS improved the current efficiency dramatically.
Figure 10. SWNT- and ITO-based OLEDs show comparable lifetime performance: (a) luminance and bias versus time for SWNT network anode-based OLED; (b) luminance and bias versus time for ITO anode based OLED. The sheet resistance is 350 and 200 Ω/sq for SWNT network and ITO, respectively.

Based on the current density of 0.12 and 0.05 A cm⁻², and the sheet resistance of 350 and 200 Ω/sq for SWNT network- and ITO-devices, the heat generated in SWNT network-based OLED is 40 times of that in ITO-based OLED. Our hypothesis is that these lifetime data mainly reflect active polymer layer properties, not failure of the anode material. The SWNT network anode achieves lifetimes similar to those of the ITO-based OLEDs. Note that all lifetime data were obtained for unencapsulated devices. One noticeable difference in lifetime properties between the SWNT network- and ITO-based OLED is at around 50 h operation time. The light output gradually declines for the SWNT network-based OLED and while that of the ITO-based OLED falls abruptly [16].

2.6. Mechanical properties of OLEDs based on ITO and CNT electrodes

The principle advantage of SWNT network electrodes for FOLED applications is the mechanical flexibility. The failure mechanism of OLED devices under strain or bending is mainly due to the cracking of the electrodes. There are several published reports on mechanical properties-performance correlations for SWNT networks in field effect transistors under strain or bending [39]. Figures 11(a) and (b) show the morphology of ITO and SWNT network films on PET after identical bending. Clearly the ITO electrode exhibits cracks along the bending direction and these cracks build up and eventually, catastrophically disrupt the surface conduction. In contrast, the SWNT network does not show any sign of electrical failure after repetitive bending, and from SEMs, there is no noticeable difference in the images before and after the bending. The mechanical flexibility of the SWNT networks is principally due to the long aspect ratios and strong interactions between individual tubes. Individual SWNTs have exceptional mechanical flexibility and generally strong interactions with the substrate [38]. Furthermore, the tubes are extensively entangled in networks which should enhance mechanical integrity. Bending cannot build up cracks in SWNT networks as in ITO electrodes. Figure 11(c) summarizes the bending test results. Clearly the SWNT network exhibits superior flexibility over ITO on PET, especially at low bending radii. Figure 11(d) shows a working OLED device under bending using the structure in figure 2 with a SWNT network as the anode material. There is no degradation in performance after bending the OLED device at a radius of 10 cm.

3. Conclusions

Due to the high work function and mechanical flexibility, SWNT networks are promising materials for FOLED applications. Here we compared the properties of SWNT networks in detail to those of widely used ITO electrodes. The light output achieved in this study already meets the display requirement (∼200 cd m⁻²). It is the first time that we investigated the effects of the relatively high SWNT sheet resistance on OLED performance. For 4 mm × 10.0 mm devices, the light output uniformity is visibly poor. However, for display applications, pixel areas of 100 μm × 100 μm are much smaller and this effect should be less pronounced. SWNT network surface morphology effects on PLED device response were also studied. The protruding nanotubes as well as the high surface roughness may be problematic for OLED applications. However, after surface morphology optimization by spin-coating with MeOH modified PEDOT, the device performance improves dramatically. The data suggest that there is much room for further optimization of OLED performance using SWNT network anodes. Future directions for transparent SWNT network implementation in OLEDs will lie in materials optimization for higher conductivity, scaling network fabrication methods, and SWNT network surface modification for better coating with subsequent layers. Due to the highly porous microstructure, incorporating other materials into SWNT networks should further smooth the surface morphology and/or incorporate other functionality. For example, low work function materials can be incorporated into SWNT networks to make them useful as cathodes in optoelectronic devices where low work functions are required.
4. Experimental details

Laser ablation-derived single-wall carbon nanotubes were used in this study. They were dispersed in water with surfactant, and the dispersion sprayed onto heated substrates. The concentration of nanotube was 1 mg l\(^{-1}\) and the concentration of sodium dodecyl sulfate (SDS) surfactant was 1 wt%. After deposition, the films were rinsed with DI water to remove excess surfactant. For PEDOT films, Baytron P was spin-coated onto the SWNT films at 2500 rpm for 1 min, followed by drying at 120\(^\circ\)C for 8 min. ITO on PET was obtained from CPFilms Inc. The optical spectra of SWNT networks, PEDOT films, and ITO were measured using another blank PET substrate as the background. Therefore, the substrate transmittance was taken into account. For bending tests, ITO films and SWNT networks on PET were mounted on mandrels of different diameters. For OLED fabrication, a polymer blend hole-transporting layer (HTL) composed of a cross-linkable, hole-transporting organosiloxane material such as TPD-Si2 and a hole-transporting polymer such as TFB (figure 2), which also serves as an effective OLED electron-blocking layer (EBL) [18], was spin-coated onto clean SWNT film or onto a PEDOT–PSS-coated SWNT film to form a double-layer HTL. These HTL films were then dried in a vacuum oven at 90\(^\circ\)C for 1–2 h. PEDOT–PSS (Baytron P) was spin-coated onto the SWNT films at 2500 rpm for 1 min, followed by drying at 120\(^\circ\)C for 8 min. Alternatively, a mixture of PEDOT–PSS and methanol (Baytron P:MeOH, 1:2 by volume) was spin-coated onto the SWNT films at 600 rpm for 1 min, then at 2500 rpm for 1 min, followed by drying at 120\(^\circ\)C for 2 h in a vacuum oven. Next, a well-balanced charge transport/emissive layer (EML), a TFB + BT blend (TFB:BT = 1:4), or an electron-dominated EML, BT [18], was spin-coated onto the HTL-coated substrates from xylene solution, resulting in an EML thickness of \(~70\) nm (figure 2). The resulting films were then dried in a vacuum oven at \(~90\)\(^\circ\)C overnight. Inside an inert-atmosphere glove box, CsF and Al were thermally evaporated onto the EML at \(<10^{-5}\) Torr using a shadow mask to define the 2.0 mm \(\times\) 5.0 mm electrode areas. The resulting OLEDs were characterized inside a sealed aluminum sample container under a dry N\(_2\) atmosphere using a computer-controlled Keithley 2400 source meter and an IL 1700 Research Radiometer equipped with a calibrated photodetector. OLED lifetime measurements were carried out using a computer-controlled Keithley 2400 source meter and an IL1400A International Light Radiometer/Photometer inside a sample container continuously purged with N\(_2\) gas at room temperature.

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