Supplementary Information

Highly efficient green, blue, and white phosphorescent inverted organic light-emitting diodes by improving charge injection and balance

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Table S1 HOMO, LUMO, triplet energy level (E_T), optical energy band-gap (E_g), and electron mobility (μ) of three different ETMs.

ETMs	HOMO (eV)	LUMO (eV)	E_T (eV)	E_g (eV)	μ ($cm^2\ V^{-1}\ s^{-1}$)	Ref.
3TPYMB	6.77	3.32	2.95	3.45	10^{-5} order	[1]
TmPyPB	6.68	2.73	2.78	3.95	10^{-3} at 6.4×10^5 V/cm	[2]
BmPyPB	6.67	2.62	2.69	4.05	10^{-4} at 3.6×10^5 V/cm	[3]

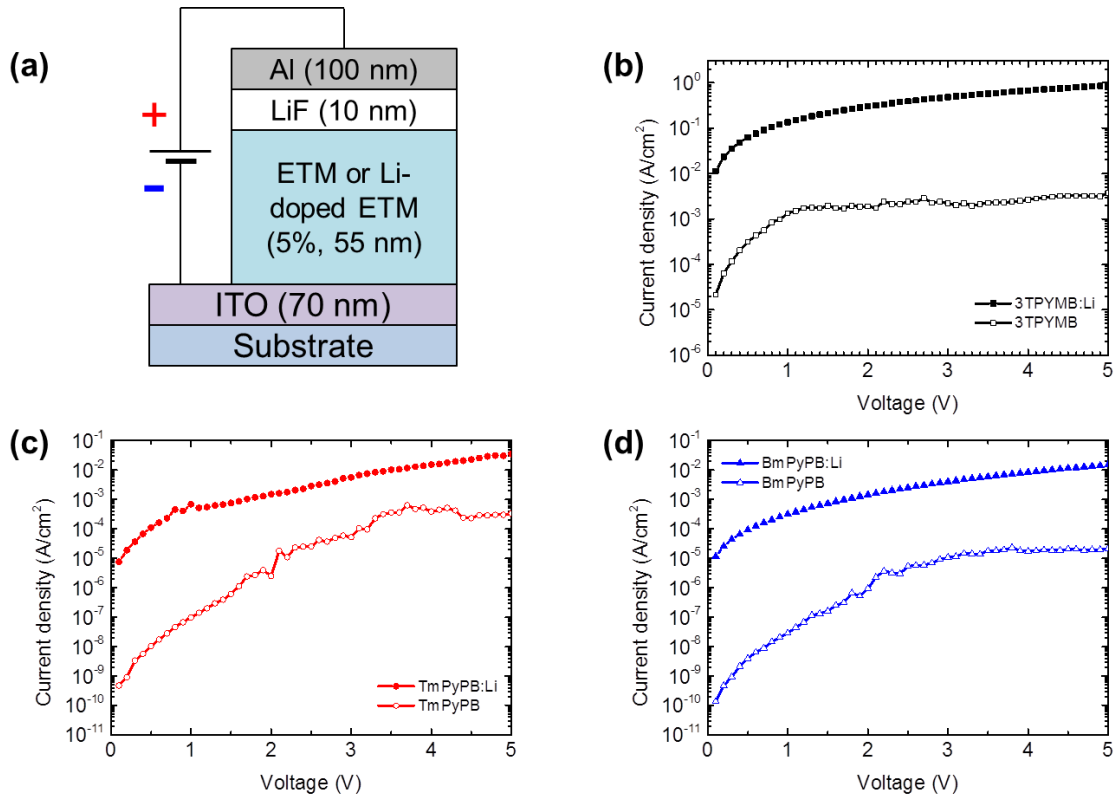

Fig. S1 (a) EOD structure with ITO as a bottom cathode for the inverted-device application, and *J*–*V* characteristics of EODs with pristine and Li-doped (b) 3TPYMB, (c) TmPyPB, and (d) BmPyPB. In these EODs, we used low thicknesses of ETMs for practical OLED application.

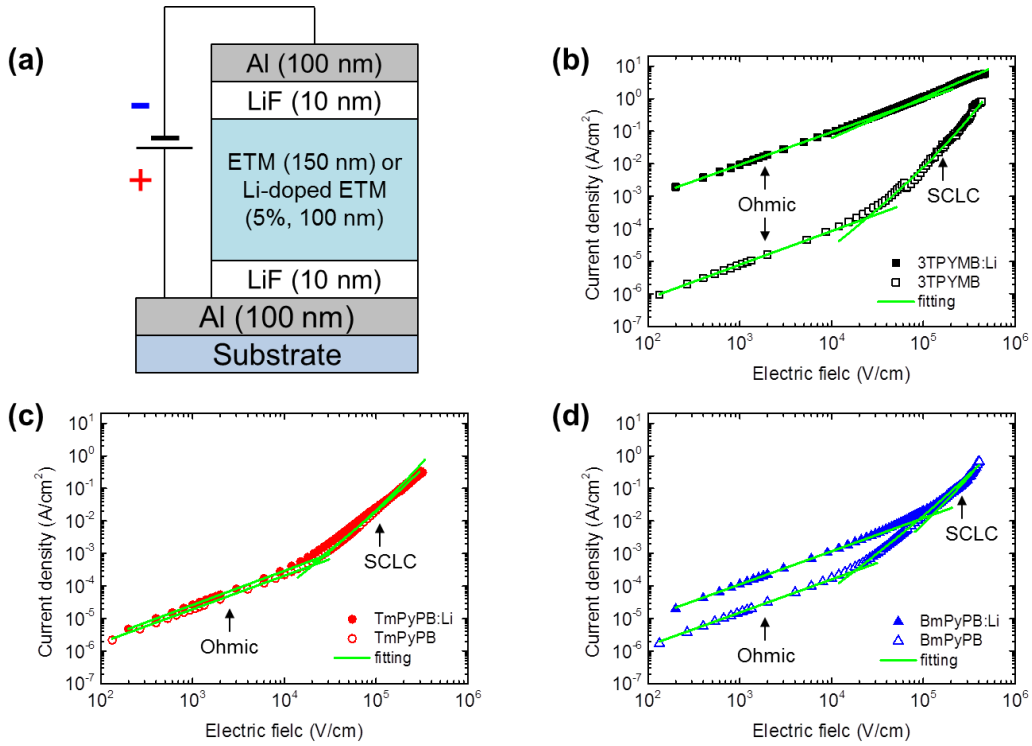

Fig. S2 (a) EOD structure with Al electrodes and *J*–*E* characteristics of EODs (Al as a top cathode) with pristine and Li-doped (b) 3TPYMB, (c) TmPyPB, and (d) BmPyPB. For SCLC fitting, charge injection should be efficient (Ohmic contact), and the interfacial effect between the electrode and the active layer should be minimized. For this reason, we additionally fabricated EODs with thicker ETMs and Al electrodes, as shown in Fig. S2(a). The Ohmic conductivities at low fields are increased by Li-doping. From the linear fitting in the Ohmic region, we can calculate the electrical conductivities of pristine and Li-doped ETMs.

Table S2 Zero-field mobility (μ_0), Poole-Frenkel slope (β), and Ohmic conductivity (σ) of pristine and Li-doped ETMs obtained from the *J*–*E* characteristics of EODs in Fig. S2.

ETMs	μ_0 (cm^2/V·s)	β ((cm/V)$^{0.5}$)	σ (S/cm)
3TPYMB	7.36×10^{-6}	5.45×10^{-3}	9.17×10^{-9}
TmPyPB	2.44×10^{-5}	4.76×10^{-3}	2.19×10^{-8}
BmPyPB	2.78×10^{-5}	2.88×10^{-3}	1.66×10^{-8}
3TPYMB:Li	-	-	9.38×10^{-6}
TmPyPB:Li	2.23×10^{-5}	3.25×10^{-3}	3.29×10^{-8}
BmPyPB:Li	5.84×10^{-6}	4.92×10^{-3}	1.22×10^{-7}

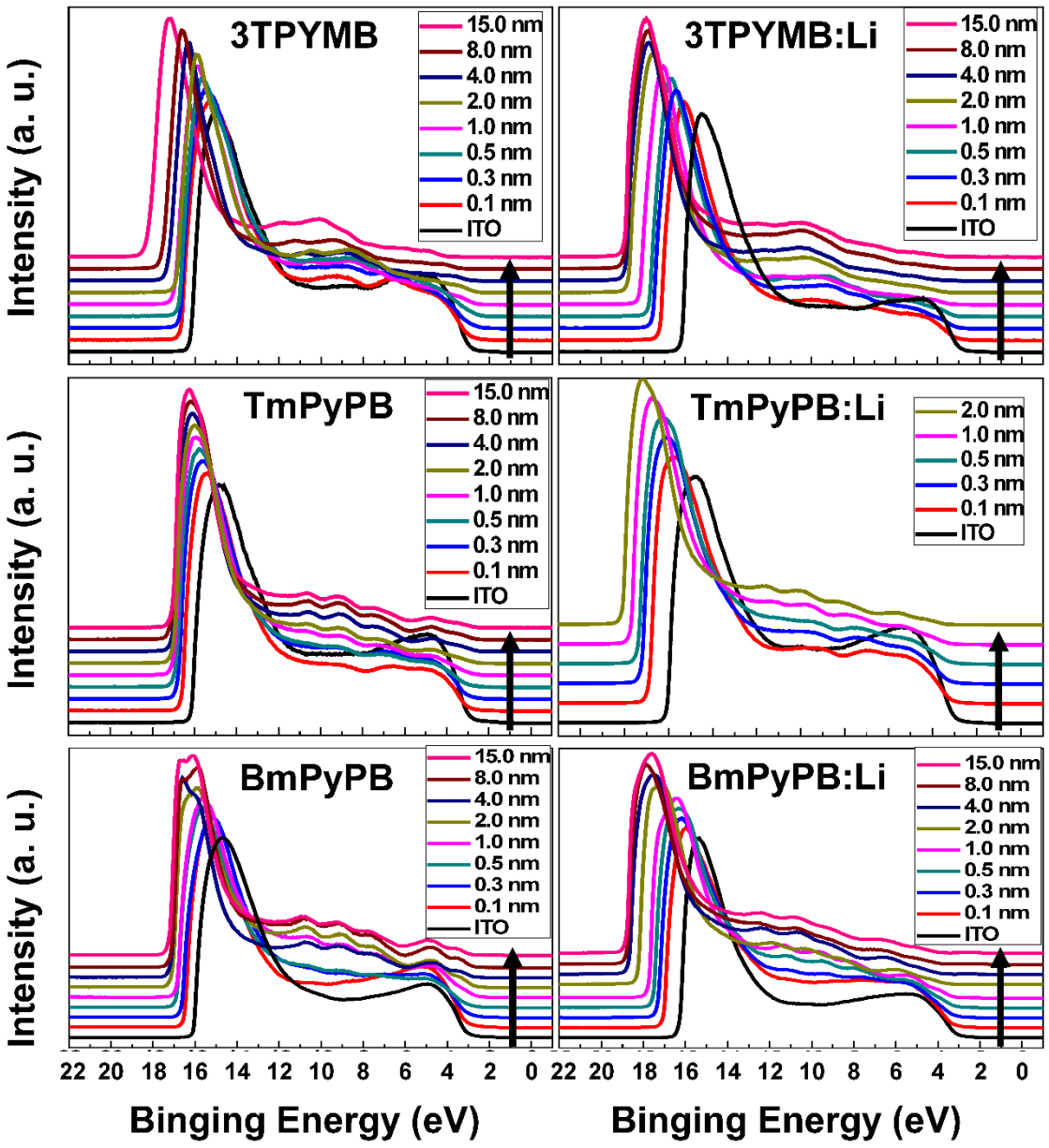

Fig. S3 UPS spectra of ITO and pristine and Li-doped ETMs with different thickness on ITO.

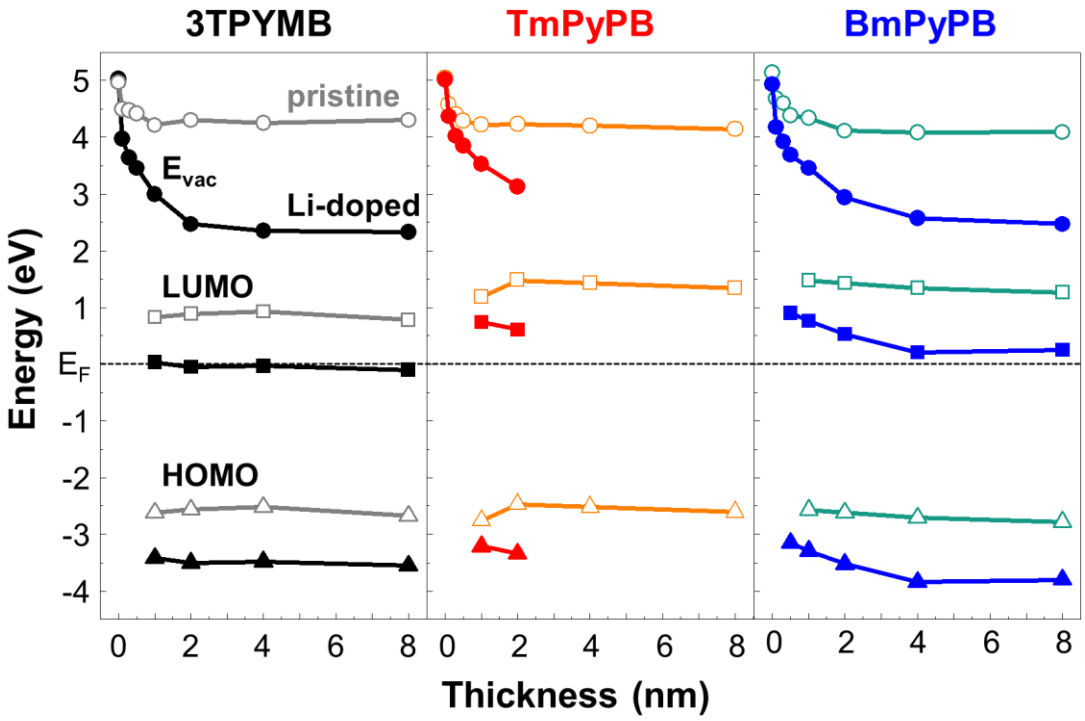

Fig. S4 Evolution of energy levels as a function of ETM thickness derived from Fig. S2. The LUMO position of each ETM was deduced from optical bandgap values, which may underestimate the real transport gap values. This is evident in the LUMO level of Li-doped 3TPYMB below the Fermi level, which should not occur in real devices.

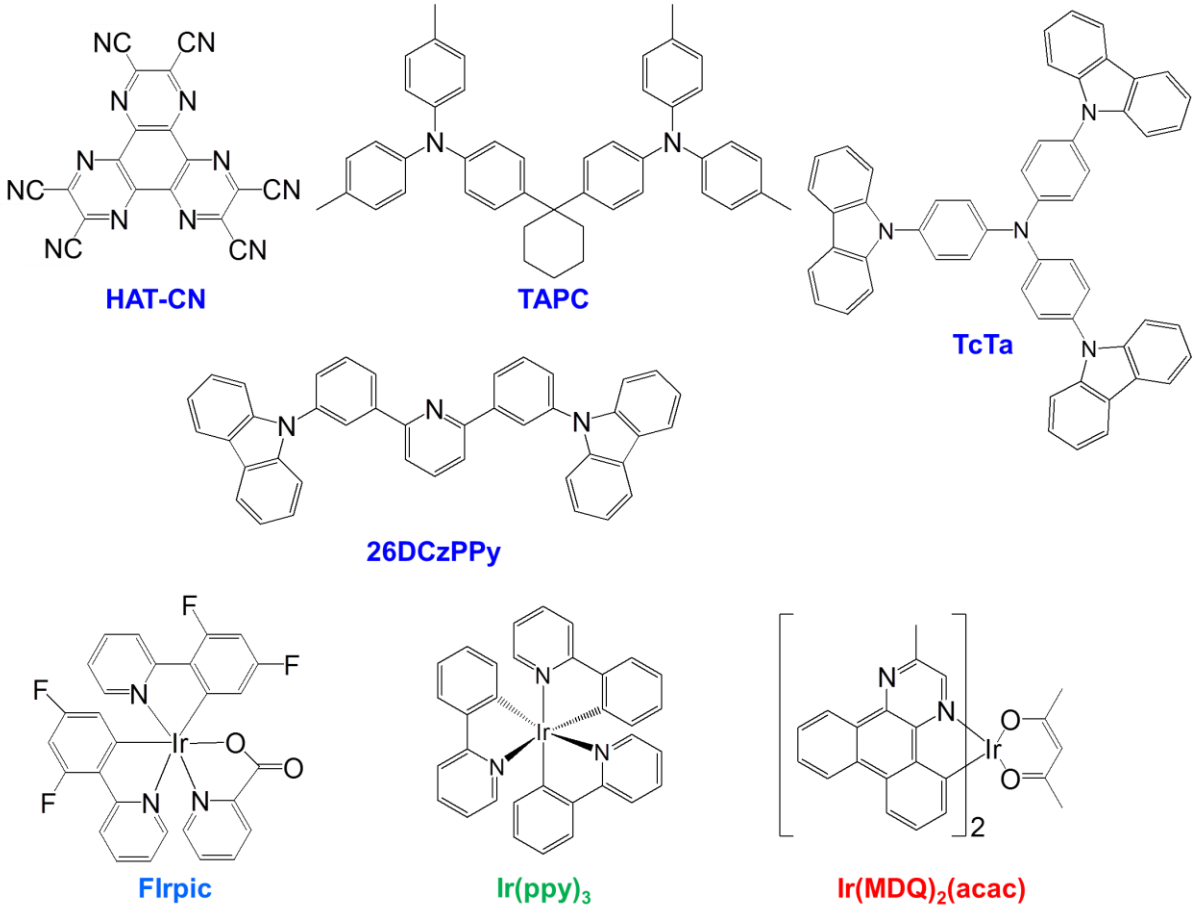

Fig. S5 Chemical structures of all the molecules used in green, blue, and white IBE-OLEDs (chemical structures of used ETMs are shown in Fig. 5).

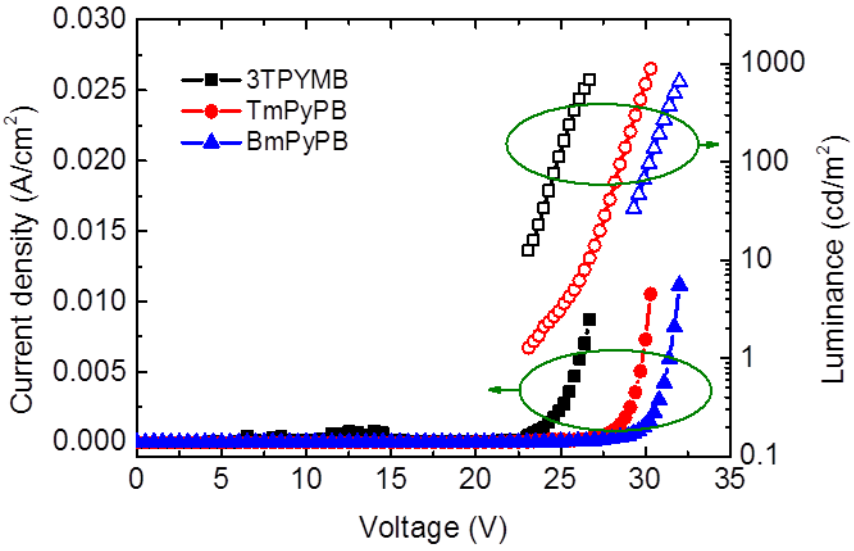

Fig. S6 *J–V–L* characteristics of green phosphorescent IBE-OLEDs with pristine ETMs as EILs.

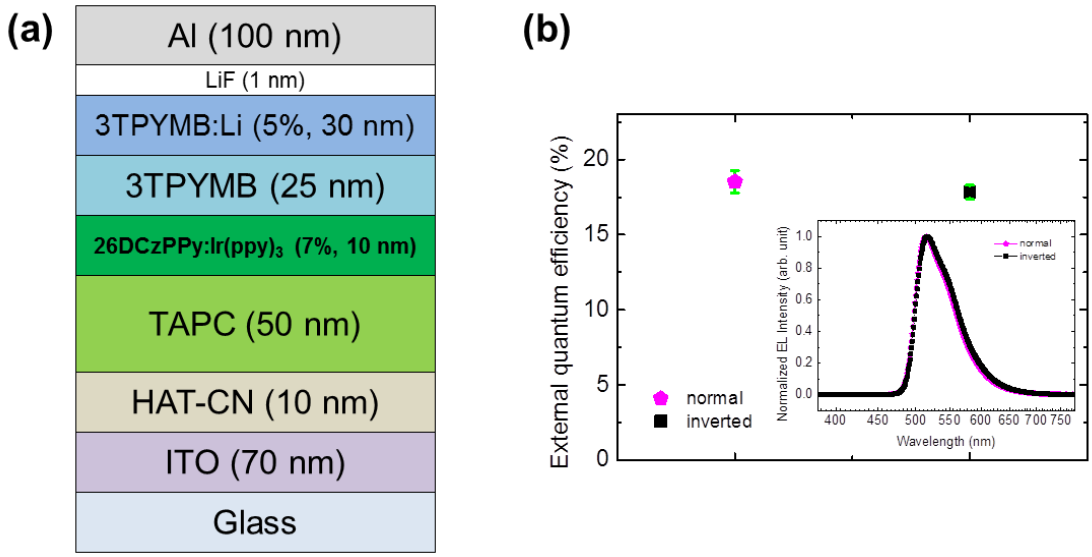

Fig. S7 (a) Green phosphorescent OLED with normal structure and (b) comparison of external quantum efficiency at the same current density of 2.5 mA/cm^2, depending on the device structure. External quantum efficiencies of normal and inverted devices were approximately 18.52±0.75% and 17.83±0.47%, respectively, and measured using an integrating sphere (HM series, Otsuka Electronics). Inset: EL spectra of green phosphorescent normal and inverted OLEDs at approximately 2.5 mA/cm^2.

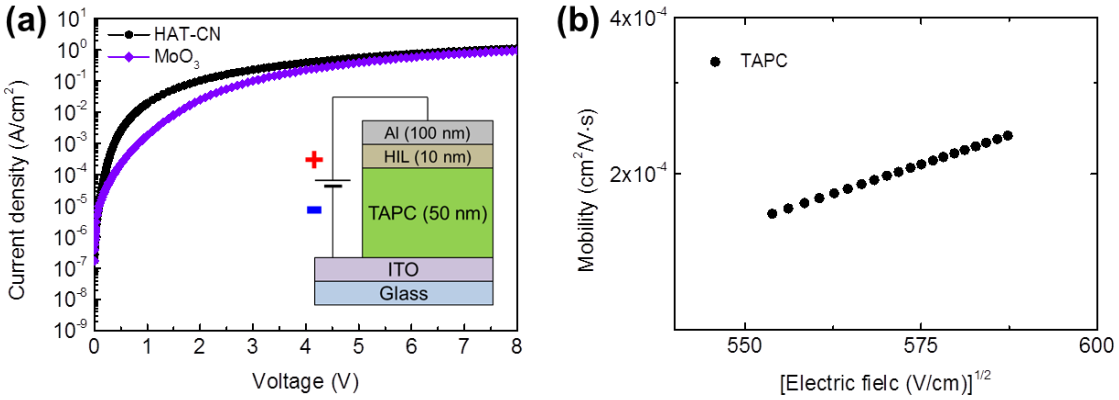

Fig. S8 (a) *J*–*V* characteristics of hole-only devices (HODs) with different HILs of HAT-CN and MoO_3 (Inset: schematic device structure) and (b) hole mobility of TAPC estimated from HODs with HAT-CN using the SCLC model [4,5]. In this HOD, we used a low thickness of TAPC (50 nm) for practical OLED application, and the hole mobility of TAPC obtained from the HOD is lower than the previously reported value estimated from time-of-flight (TOF) measurement. This may be due to the different device structure and low thickness of TAPC compared with the TOF device (thicknesses of TAPC were between 6 and 11 μm) [6,7]. The low hole mobility of TAPC in this structure improves electron-hole charge balance, resulting in high efficiency because the electron mobilities of ETMs used in this work are of similar orders of magnitude, as shown in Fig. 1(b).

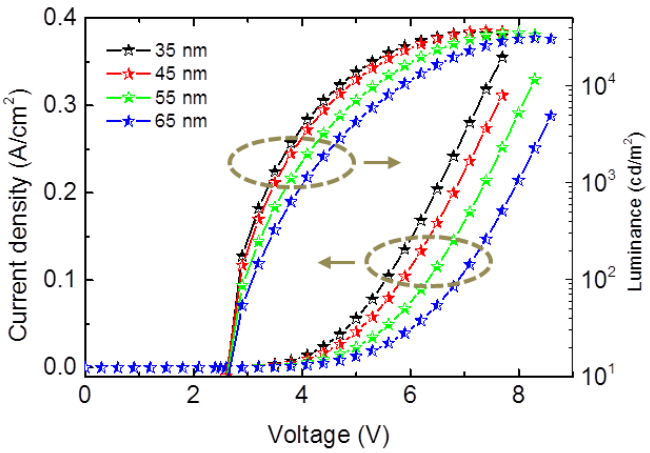

Fig. S9 *J*–*V*–*L* characteristics of white phosphorescent IBE-OLEDs depending on TAPC thickness.

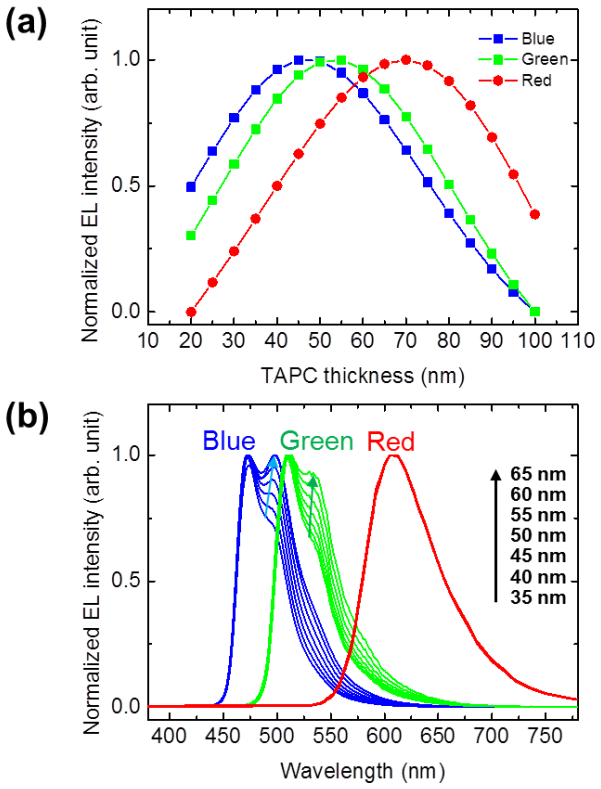

Fig. S10 Optically simulated EL (a) intensity and (b) spectra of blue, green, and red OLEDs depending on TAPC thickness.

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