Supplementary Information

Improving the Air Stability of Flexible Top Emitting Organic Light-Emitting Diodes by Silver

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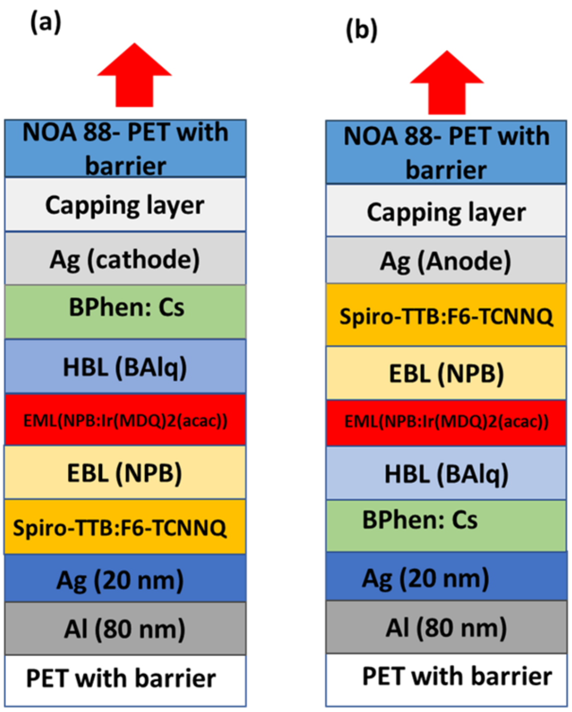
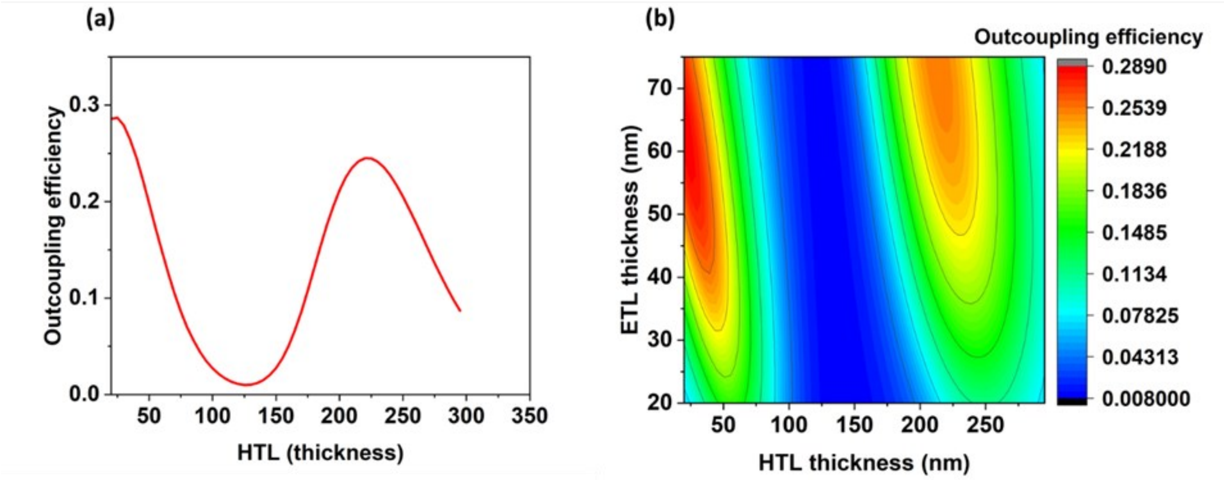
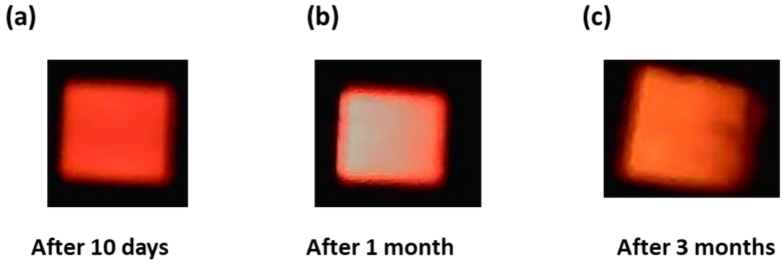


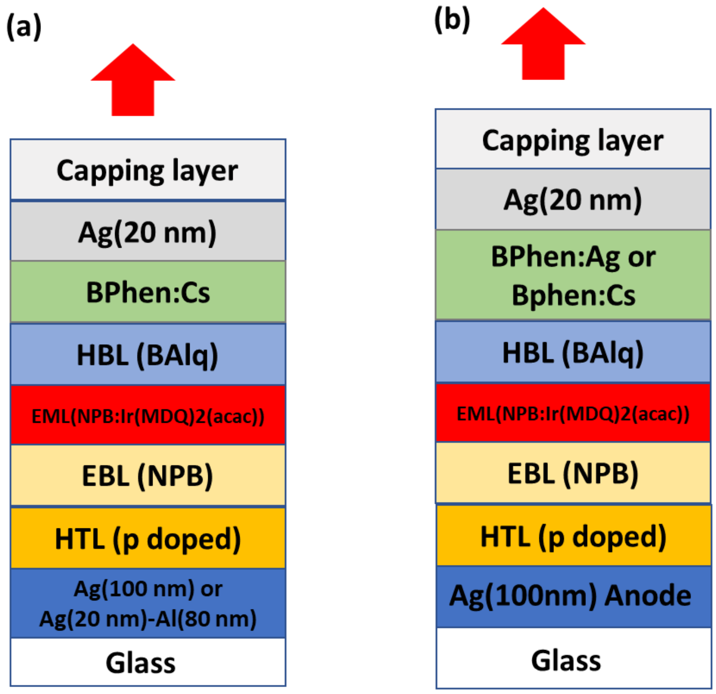
Supplementary Figure 1. Device structures. a) p-i-n structure using Al/Ag for the bottom reflective electrode. b) n-i-p structure with Al/Ag reflective electrode.



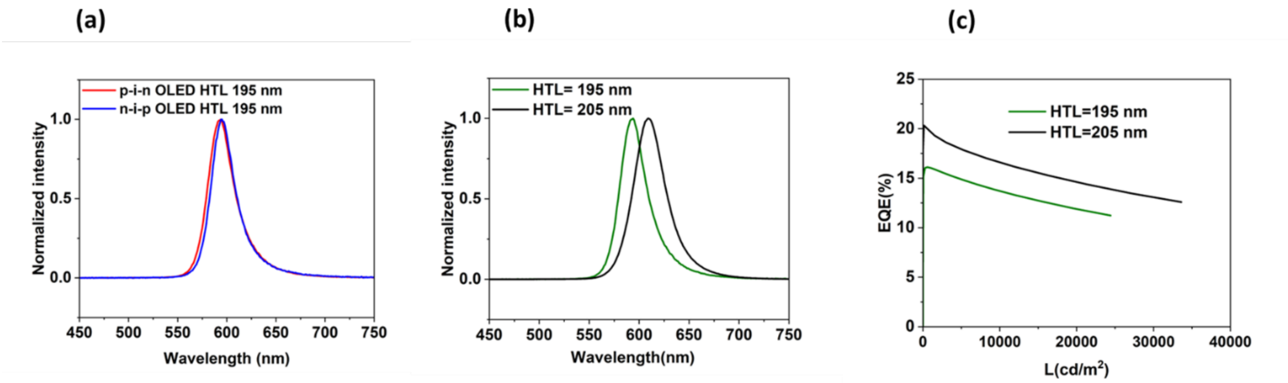
Supplementary Figure 2. a) Outcoupling efficiency calculation as a function of HTL thickness using p-i-n structure and ETL thickness of 60 nm. b) Outcoupling efficiency calculation as a function of HTL and ETL thicknesses.



Supplementary Figure 3. Photographs of the OLED using Al/Ag electrode and second order cavity. a) 10 days after fabrication b) 1 month after fabrication. c) 3 months after fabrication.



Supplementary Figure 4. Device structures. a) Comparing Ag/Al with Ag reflective electrodes. b) Comparing BPhen: Ag with BPhen: Cs electron transport layer.



Supplementary Figure 5. a) Spectrum of OLEDs using p-i-n and n-i-p structure. b) Comparison of emission spectrum by changing HTL thickness from 195 nm to 205 nm for p-i-n OLEDs. c) Comparison of EQE as a function of luminance by changing HTL thickness from 195 nm to 205 nm for p-i-n OLEDs.

Supplementary Table 1. Comparison of previously reported flexible OLEDs

Device structure	Encapsulation	Turn on or operating voltage	EQE or current efficiency	Shelf lifetime	Advantages	Limitations
Polymer light emitting diode (PLED) Bottom emitting-ITO-ZnO (inverted structure)[1]	Without encapsulation	Turn on voltage 4.7 V operating voltage of 6V	14 cd/A at 24 mA/cm^2	40 hours	Without using any stringent encapsulation techniques (easier and faster to fabricate the devices)	Low shelf lifetime-High operating and turn on voltages-High evaporation temperature of ZnO- Limit the choice of using substrate to (ITO) to match with ZnO work function
Bottom emitting Parylene/ITO/ZnO[2] (inverted structure)	Parylene	5 V at 1000 cd/m^2	20 %	70 hours	Same as above	Same as above

Bottom emitting OLED ITO-ZnO-interlayer[3] (inverted structure)	lamination	Operating voltage 5 V at (1000 cd/m^2)	EQE 13% using Ir(piq)$_3$	Only few dark spots but no shrinkage after 1 year	Good shelf lifetime	High operating voltage-Low EQE-Mechanical damage caused by laminator can affect device's yield. Using an interlayer which requires solution coating and annealing processes between the vacuum processes in OLED fabrication-High evaporation temperature of ZnO- Limit the choice of using substrate to (ITO)-
Both bottom and top emitting OLEDs[4]	Parylene/ALD/ Parylene /ALD	3.5 V at 1000 cd/m^2	EQE of 22%	70 days	Good EQE and shelf lifetime-ITO free OLEDs	Complex and time-consuming encapsulation techniques-Increasing the temperature during ALD process can affect device performance.
Top emitting fluorescent OLED [5]	ALD/ UV-curable cycloaliphatic epoxy hybrid materials	5.5V at 1000 cd/m^2	Current efficiency of 4 cd/A	30 days	No reliance on ITO substrate	High operating voltage- low shelf lifetime (protection with one deposition cycle of ALD is not enough)

Supplementary Note 1- Details of optical modelling

To explain the improvement in device efficiency by replacing aluminium with silver we performed calculations as shown in Figure 4 of the main manuscript. The calculations of outcoupling efficiency and optical loss were done by modelling the emission dipole of the emitter molecules as a forced-damped harmonic oscillator embedded in a thin film stack. The principle of the calculation has been described in previous studies[6–8], and we used the mathematical equations in Ref (6). The calculation was done from 400 nm to 800 nm with a 1 nm step at each wavelength. We calculated the power dissipated by the dipole for the normalized in-plane wave vector from 0.0 to 2.0 with a 0.002 step. To make sure that the calculation captures the dissipation into all evanescent modes in the OLEDs the maximum wave vector was chosen which is wider than the range used in the previous study for the simulation of OLEDs in Ref (6). Calculation of out-coupling efficiency (η_{out}) was done by taking the ratio of the power outcoupled into air (P_{out}) to the total dissipated power (P_{tot}), i.e., η_{out} = (P_{out} /P_{tot}). Calculation of optical loss due to absorption and reflection (Abs+Ref losses, $\eta_{abs+ref}$) was done first by taking the ratio of dissipated power from 0 to the normalized-in plane wave vector (k_{air}) corresponding to the critical angle between the emission layer and air (P_{air}) to total dissipated power (P_{tot}) and then subtracting the outcoupling efficiency from the ratio, i.e., $\eta_{abs+ref}$ = (P_{air} / P_{tot}) - η_{out}. Calculation of the fraction of light trapped in the waveguide (WG) mode and the surface plasmon polariton (SPP) mode (η_{SPP+WG}) was done by calculating the ratio of the dissipated power integrated from k_{air} to the maximum wavevector (P_{SPP+WG}) and then dividing P_{SPP+WG} by the total dissipated power i.e., η_{SPP+WG} = (P_{SPP+WG} / P_{tot}). For clarity, it is noteworthy to mention that $\eta_{out} + \eta_{abs+ref} + \eta_{SPP+WG} = 1$.

The reported value of emission dipole anisotropy factor of the emitter molecules is 0.23-0.25 in Ref. [9] and the value of 0.23 was used in our calculation. Because NPB was used for the host molecule in the emission layer which has a good hole transport property we assumed charge recombination is localized at the interface between the hole blocking layer and the emission layer. Therefore, in the calculation we placed the emission dipole in the NPB layer just next to the hole-blocking layer.

Abs+Ref loss in **Figure 4c** shows the ratio of light with a propagation angle less than the critical angle of the emission layer/air interface that could not outcouple owing to losses caused by electrodes (absorption and imperfect reflection) versus total light generated. As mentioned on page 6 of the main manuscript Abs+Ref losses are reduced by changing the bottom reflective electrode from Al (80 nm)-Ag (20 nm) to Ag (100 nm). Because coupling to waveguide (WVG) modes and surface plasmon polariton (SPP) modes does not change by changing the reflective electrode (Figure 4d) the improvement in outcoupling and therefore EQE is mainly due to the reduction of absorption and reflection loss.

Supplementary References

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