Transparent light-emitting devices

SIR — Organic light-emitting devices (OLEDs), which emit in the red[1], green[2] and blue[3] spectral regions, have recently become promising candidates for colour flat-panel display pixels owing to their high luminosity and low operating voltage. Furthermore, long device lifetimes[4] (exceeding 1,000 hours at a video brightness of ~100 cd m^{-2}) have been demonstrated. One unique property of vacuum-deposited OLEDs is that the luminescence band is substantially red-shifted from the absorption band[5], rendering the organic layers highly transparent to their own luminescence and throughout most of the visible spectrum.

Here we demonstrate a new class of OLEDs, which are greater than 70% transparent when turned off, and emit light from both top and bottom surfaces with up to 0.75% quantum efficiency when turned on. Such transparency offers the potential for very high-definition, full-colour displays in which the red (R), green (G) and blue (B) emission layers are placed in a vertically stacked geometry, providing a simple, low-temperature fabrication process, as well as minimum R–G–B pixel size and maximum fill factor. Further applications of this device include low-voltage, semi-transparent displays for helmet-mounted, windscreen-mounted or other 'head-up' applications.

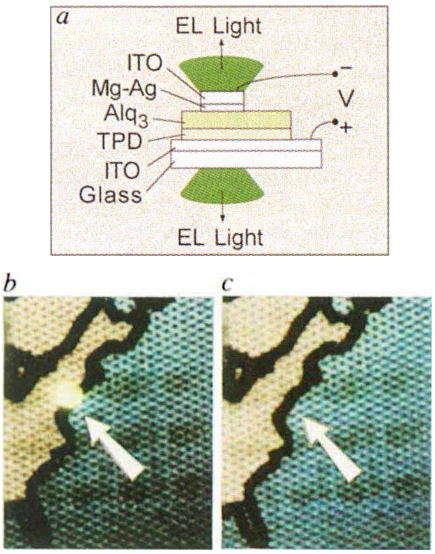

FIG. 1 *a*, Schematic diagram of the TOLED structure (ITO, indium tin oxide). *b*, An array of TOLEDs with one device turned on (green spot) against a backdrop of the eastern US coastline. Typical operating conditions for the 1-mm-diameter devices are 10^{-4} A and 10 V drive voltage. The emission spectra from both surfaces are similar to those of conventional Alq_3-based devices[2,5], after accounting for absorption in the Mg–Ag layer. The total quantum efficiency of light emission from this device is 0.75%. Approximately 10% higher intensity is emitted from the substrate than from the top contact surface. *c*, The same array with all devices turned off, demonstrating the device transparency.

The transparent OLED (TOLED) structure is shown in Fig. 1*a*. The device is grown on a glass substrate pre-coated with a thin film of transparent indium tin oxide, with a sheet resistivity of 20 Ω per square. Before deposition of the organic films, the substrates were pre-cleaned as discussed elsewhere[5]. Deposition was performed by sublimation, in a vacuum of $<10^{-6}$ torr, of a 200-Å-thick layer of the hole-conducting compound *N,N'*-diphenyl-*N,N'*-bis(3-methylphenyl)-1-1'-biphenyl-4,4'-diamine (TPD), followed by a 400-Å-thick layer of the electron-conducting and highly electroluminescent tris(8-hydroxyquinoline) aluminium (Alq_3).

Figure 1*a* shows how electron-injecting contact to the device was made by deposition through a shadow mask of a thin layer (50–400 Å) of Mg–Ag alloy (in an approximate atomic ratio of 40 Mg:1 Ag). Finally, the device was capped by a second 400-Å-thick layer of indium tin oxide, sputter-deposited onto the Mg–Ag surface to provide a continuous, transparent conducting surface. The sheet resistance of this layer is 400 Ω per square, which acts in parallel to the Mg–Ag sheet resistance and is adequate to serve as an injecting contact for a display pixel.

Figure 1 shows a photograph of a TOLED array with a 100-Å-thick Mg–Ag layer. In Fig. 1*b*, one TOLED array element is switched on (arrow) and the inactive devices are only faintly visible. They reduce the light from the background by only ~3 dB, even though these images are taken under the condition that the light illuminating the background must pass twice through the TOLED. In Fig. 1*c*, all the elements are switched off. The transparency as a function of a TOLED from this array is shown in detail in Fig. 2. The device becomes non-transmissive at short wavelengths owing to a combination of Mg–Ag absorption and the strong molecular transitions to the ^1L_a and ^1B_b states[6] of Alq_3, and at long wavelengths due to absorption by the Mg–Ag. However, the device is 63% transparent at the peak (530 nm) emission wavelength of Alq_3, and this transparency extends across the visible spectrum.

The inset to Fig. 2 shows the transmission of the Mg–Ag contact at a wavelength of 530 nm, with Mg–Ag film thicknesses ranging from (50±10) Å to (400±10) Å. The thinnest Mg–Ag layer used thus far in a working device is 75 Å thick, corresponding to a contact transparency of 81% and a total device transparency of 71%. The real and imaginary coefficients of the refractive index of Mg at 530 nm are $n=0.57$ and $k=3.47$, respectively[7]. Neglecting the small amount of Ag in the electrode, we calculate that an 81% transmissive film of Mg should be 15 Å thick. This suggests that approximately (60±10) Å of the Mg–Ag electrode is compositionally changed in the deposition process, presumably due to a redox reaction with indium tin oxide during sputtering. This explains the higher measured transparency, the departure of our transmission versus thickness data from a straight line, and our inability to produce working devices with less than a 75-Å-thick layer of Mg–Ag.

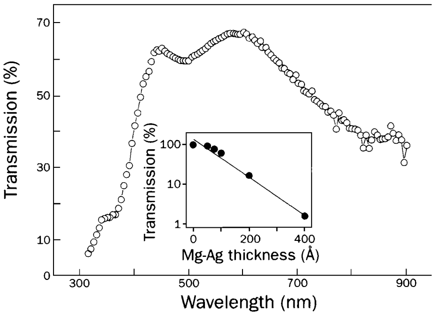

FIG. 2 Transmission spectrum of a TOLED with a 100-Å-thick Mg–Ag electrode as a function of wavelength. Inset, Transmission as a function of Mg–Ag contact thickness at a wavelength of 530 nm. The slope of the straight line fit to the data gives an optical absorption coefficient of the Mg–Ag of $\alpha=1.1\times10^6$ cm^{-1}, consistent with a calculated skin depth of 125 Å.

In conclusion, we have demonstrated the first transparent, thin-film organic light-emitting devices. This is the crucial first step towards realizing high-definition, full-colour and head-up displays using organic materials.

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