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.

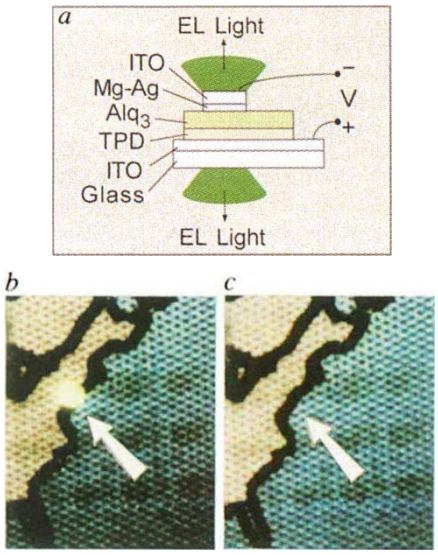

FIG. 1 *a*, Schematic diagram of the TOLED structure (ITO, indium tin oxide). *b*, An array of TOLEDs with one device turned on (green spot) against a backdrop of the eastern US coastline. Typical operating conditions for the 1-mm-diameter devices are 10^{-4} A and 10 V drive voltage. The emission spectra 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.

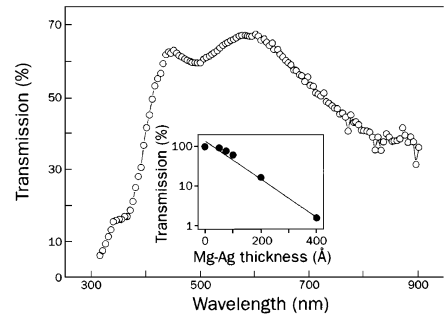

FIG. 2 Transmission spectrum of a TOLED with a 100-Å-thick Mg–Ag electrode as a function of wavelength. Inset, Transmission as a function of Mg–Ag contact thickness at a wavelength of 530 nm. The slope of the straight line fit to the data gives an optical absorption coefficient of the Mg–Ag of $\alpha=1.1\times10^6$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

V. Bulović
G. Gu
P. E. Burrows
S. R. Forrest
Advanced Technology Center for Photonics and Optoelectronic Materials, Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544, USA
M. E. Thompson
Department of Chemistry, University of Southern California, Los Angeles, California 90089, USA

1. Takada, N., Tsutsui, T. & Saito, S. *Japan. J. appl. Phys.* **33**, L863–L866 (1994).
2. Tang, C. W. & VanSlyke, S. A. *Appl. Phys. Lett.* **51**, 913–915 (1987).
3. Adachi, C., Tsutsui, T. & Saito, S. *Appl. Phys. Lett.* **56**, 799–801 (1990).
4. Burrows, P. E. *et al. Appl. Phys. Lett.* **65**, 2922–2924 (1994).
5. Burrows, P. E. & Forrest, S. R. *Appl. Phys. Lett.* **64**, 2285–2287 (1993).
6. Garbuzov, D. Z., Bulović, V., Burrows, P. E. & Forrest, S. R. *Chem. Phys. Lett.* (in the press).
7. O'Bryan, H. M. *J. opt. Soc. Am.* **26**, 122–127 (1936).

SDC EX. 1022 - 1/1