

reduction in thickness which resulted in a concomitant reduction in the non-metallic-cathode-containing TOLED fabrication yield from about 90% to 40%. The fabrication yield is defined as the ratio of the non-shortcd, efficient devices to the total number of devices fabricated and tested. Such yields were based on test populations of 10 to 20 test devices. These results suggests that only the first few monolayers of the CuPc are damaged in low resistance cathode/organic layer interfaces, as was shown in the case of ITO/PTCDA. It is thought that when the CuPc is made too thin, the sputtered ITO can "punch through" to damage the underlying Alq₃. Indeed, ITO sputtered directly onto either α -NPD or Alq₃, wherein the ITO layer would function as an anode or a cathode, respectively, results in a yield approaching zero.

[0073] It is believed herein that the limited damage to CuPc and PTCDA may be due to the extended conjugated electron orbitals in these large planar molecules. When an energetic metal or oxygen atom is incident on one of these surface molecules during sputtering, the energy of impact is efficiently distributed over the numerous bonds in the molecular π -electron systems. In contrast, no comparably large π -electron systems exist in Alq₃ or α -NPD. For such molecules, the impact energy is more localized among only a few atomic sites, thereby increasing the probability for breaking a molecular bond. The planar or nearly planar stacking arrangements of crystalline molecular systems such as CuPc and PTCDA may also assist in the dissipation of energy among several neighboring molecules in the lattice.

[0074] This hypothesis, based on the role played by energetic atom-induced defects in assisting carrier injection, was tested by fabricating a transparent non-metallic-cathode-containing TOLED such as that shown in **FIG. 12**, except with the Alq₃ and α -NPD layer order reversed. For these devices having the ETL and HTL layers reversed, V_T was observed to increase by a factor of two ($\sim 10V$) and an external quantum efficiency η of about $10^{-3}\%$ was measured even though the ITO/CuPc interface is known to be excellent for injecting holes into α -NPD. The low efficiency of this device, therefore, provides clear evidence that an CuPc/ITO interface not having the damage layer is ineffective in injecting electrons into Alq₃. It is, therefore, concluded that the low energy deposition of CuPc on top of ITO does not generate the interfacial mid-gap states required for electron injection. Thus, since the ITO layers prepared by Karl et al and Whitlock et al were also produced by deposition of the organic layer onto the ITO layer, rather than by deposition of the ITO layer onto the organic layer so as to produce a damage layer, the ITO layers of Karl et al and Whitlock et al would be expected also not to produce the enhanced electron-injection characteristics of the present invention, whenever the electrodes of Karl et al or Whitlock et al functioned as the cathode of a solar cell.

[0075] The asymmetry in the device characteristics is also consistent with the very low current and lack of electroluminescence when the non-metallic-cathode-containing TOLED is reverse biased. In this case, the electrons are unable to traverse the 1.6 eV energy barrier from the ITO into the undamaged CuPc at the anode. Once electrons are injected into the CuPc, they are transported into the Alq₃ due to the lack of an energy barrier to electron transport in that direction. In contrast, a large energy barrier to electrons of 0.9 eV exists from PTCDA to Alq₃. This barrier, coupled

with the poor electron mobility of PTCDA, results in the observed high V_T and low η of Alq₃-based devices employing ITO cathodes in contact with PTCDA. This low efficiency does not, however, suggest that PTCDA cannot be used to make a good low resistance cathode/organic interface. In particular, these results only show that a barrier of 0.9 eV is too high between the PTCDA and the Alq₃. By properly matching the PTCDA with an appropriate adjacent charge-carrying layer, in accord with the guidelines provided herein for aligning the LUMO/HOMO levels, an efficient ITO/PTCDA interface may be made.

[0076] As an example of another representative OLED embodiment of the present invention, the non-metallic cathode may be used in a double heterostructure wherein a thin luminescent layer is present between the electron transporting layer and the hole transporting layer.

[0077] As another representative OLED embodiment in which an electron transporting layer is the emissive layer, the ITO layer may be in contact with the electron injecting interface layer that produces the electroluminescence and that, in addition, is in direct contact with a hole transporting layer. In this case, the IP-HOMO/LUMO gap energy of the material used in the electron injecting interface layer is such that it is approximately equal to or preferably less than the IP-HOMO/LUMO gap energy of the material in the adjacent hole transporting layer and, in addition, the ionization potential of the material in the hole transporting layer is greater than the ionization potential of the material used in the electron injecting interface layer.

[0078] As a representative embodiment of the invention in which the hole transporting layer is the emissive layer, the ITO layer may be in contact with an electron injecting interface layer that is in direct contact with a hole transporting layer that produces the electroluminescence. In this case, the IP-HOMO/LUMO gap energy of the material used in the electron injecting interface layer is also such that it is approximately equal to or preferably less than the IP-HOMO/LUMO gap energy of the material in the adjacent hole transporting layer. However, in this case, the ionization potential of the material in the hole transporting layer is less than the ionization potential of the material used in the electron injecting interface layer. Thus, while the present invention is demonstrated for a single heterostructure in which the ITO layer is in contact with an electron injecting interface layer that is in contact with an electron transporting layer such as Alq₃, the present invention is directed toward any OLED comprised of a heterostructure for producing electroluminescence wherein the heterostructure includes a non-metallic cathode.

[0079] In particular, the OLEDs of the present invention are comprised of a heterostructure for producing electroluminescence which may be fabricated as a single heterostructure or as a double heterostructure. The materials, methods and apparatus for preparing the organic thin films of a single or double heterostructure are disclosed, for example, in U.S. Pat. No. 5,554,220, which is incorporated herein in its entirety by reference. As used herein, the term "heterostructure for producing electroluminescence" refers to a heterostructure that includes, for a single heterostructure, in sequence, a hole injecting anode layer, a hole transporting layer, an electron transporting layer, and a cathode layer. An additional layer or layers may be present between one or