

## An Electrically Conducting Structure For A Light Transmissible Device

### FIELD OF INVENTION

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The present invention relates broadly to an electrically conducting structure for a light transmissible device and to a method of forming an electrically conducting structure for a light transmissible device.

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### BACKGROUND

For devices such as top-emitting organic light-emitting diodes (OLEDs), ultrathin metal films are typically used as transparent cathodes. However, the ultrathin metal cathodes, e.g. Mg:Ag, LiF/Al, LiF/Al/Ag, Ca/Ag etc, typically exhibit low resistance to moisture and oxygen resulting in a short device lifetime. Further, ultrathin metal cathodes typically cause a relatively high amount of internal reflection at the electrode/air interfaces due to the mismatch of the refractive indexes at the cathode/air interface. In addition, ultrathin metal cathodes typically have high absorption in the visible light wavelength region that can lead to low transmittance.

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Therefore, technologies have progressed to forming a covering layer of transparent conducting oxides (TCOs) over metal cathodes, thus giving rise to metal/TCO-based cathodes.

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Thin films of TCOs have many applications due to their properties of e.g. good electric conductivity and high optical transparency in the visible spectrum range. Doped oxide materials, e.g. ZnO, SnO<sub>2</sub> and In<sub>2</sub>O<sub>3</sub>, are typically used individually, in separate layers or as mixtures such as indium tin oxide (ITO) and indium zinc oxide (IZO) for making TCO thin films. From the plurality of TCO thin films, ITO, aluminium-doped ZnO (AZO) and fluorine-doped SnO<sub>2</sub> (FTO) are more commonly used TCO materials. TCO is typically used as an integral part of device applications, such as anti-static coatings, heat

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mirrors, solar cells, flat panel displays, sensors, and organic light emitting diodes (OLEDs) etc.

TCO layers are typically used in cathodes in top-emitting organic/polymer light-emitting diodes (OLEDs/PLEDs) or as a charge recombination zone in tandem structure organic photovoltaic cells. The TCO layers can be used to provide an interface with organic and other materials and also act as an electrical contact. Therefore, for organic electronics, it is desired to deposit a high performance TCO-based transparent electrode on organic layers without damaging the underlying functional materials. In addition to typical TCO characteristics of e.g. transparency and conductivity, it is desired to have an electrode produced using low process temperatures and using increased process flexibility such as high-rate production, high electrode conductivity and low cost.

However, typical metal/TCO-based cathodes encounter a number of problems. For fabricating high conductivity and transparent TCO films on glass substrates, a process temperature of more than 200°C is typically required. It has been recognised that TCO films formed at process temperatures below 100°C typically have relatively higher resistivity and lower optical transparency than TCO films prepared at a substrate temperature of more than 200°C. Typically, TCO-based transparent electrodes are deposited on active materials/layers that may not be compatible with a high process temperature. For example, ITO films made by DC/RF magnetron sputtering typically require heating substrates at elevated temperatures during film preparation or adding an additional post annealing treatment at a temperature above 200°C. One problem is that high process temperatures are unsuitable for applications in organic electronics. For instance, tandem organic photovoltaic (PV) cells and top-emitting OLEDs are typically not compatible with a high temperature plasma process.

Further, in addition to damage due to high process temperatures, there are other challenges associated with deposition of TCOs. For example, ITO, one of the TCOs, is typically used as an anode/cathode material. When an ITO cathode contact is deposited on organic electron acceptors in tandem photovoltaic cells or electroluminescent materials in top-emitting OLEDs, the ITO electrode formed by the typical sputtering process may encounter the following. The device performance typically deteriorates due

to damage to underlying functional polymer/organic layers which is induced by the ITO deposition. Further, for a semitransparent cathode with an electron injector and a conducting metal layer, an index matching layer is typically required to improve the current spreading and light output coupling efficiency.

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In addition, a transparent cathode for organic electronics is typically desired to be fabricated at a relatively high deposition-rate, at low process temperatures with no or little damage to the underlying functional materials. The transparent electrode is desired to have properties of high optical transparency, high electrical conductivity, smooth surface morphology and high stability. Further, it is desired to have a scaleable process for mass production at low-cost.

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Thus, among the above-mentioned challenges, it has been recognised that, for typical metal/TCO-based cathodes, TCO deposition induces damage to underlying functional layers. Further, typical metal/TCO-based cathodes suffer from low deposition rates. In G.Gu et al, Appl.Phys.Lett.68 (19),1996, (2606-2608), RF-sputtered ITO Cathode, Ar/O<sub>2</sub>, it was found that the growth rate of the cathode was below 1.0 nm/min. Further, it was found that the metal/ITO-based cathode exhibits a relatively high sheet resistance  $R_s$ . Thus, for typical metal/TCO-based cathodes, a thicker metal layer is used to compensate for poor TCO conductivity. This can lead to a further decrease in optical transparency and possible increased cost.

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In a bid to counter the problems arising from using typical metal/TCO-based cathodes, an organic-buffer layer/TCO cathode has been suggested. Typically, a metal interlayer is not used in an organic-buffer layer/TCO cathode. This was investigated in US6569697B2, US6420031B1, G.Parthasarathy et al, Appl.Phys.Lett.76 (15),2000, (2128-2130), Haiying Chen et al, IEEE Electron Device Letters 24 (5), 2003,(315-317) and Ho Won Choi et al, Appl.Phys.Lett., 2005, 86 (012104). However, fabrication of an organic-buffer layer/TCO cathode may give rise to a number of problems including the following. As an organic buffer layer is required, the fabrication process may be more complex. Further, because of factors such as electrical properties, optical properties and work function matching, there is limited materials choice for forming the organic buffer layer. In addition, it has been found that an organic-buffer layer/TCO cathode typically

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gives rise to an increased contact resistance causing an imperfection of the carrier collection/injection property at organic/cathode interface.

Therefore, in view of the above, there exists a need for an electrically conducting structure for a light transmissible device and a method of forming an electrically conducting structure for a light transmissible device that seek to address at least one of the above problems.

## 10 SUMMARY

In accordance with a first aspect of the present invention, there is provided an electrically conducting structure for a light transmissible device, the structure comprising, a first transparent conducting material layer formed over underlying functional material using first process conditions, the first process conditions comprise a first deposition power and a first deposition temperature; at least one other transparent conducting material layer formed directly on the first transparent conducting material layer, said at least one other transparent conducting material layer being formed using second process conditions that are different from the first process conditions, the second process conditions may comprise a second deposition power and a second deposition temperature; wherein the first process conditions may be chosen such that adverse effects to the underlying functional material are reduced during formation of the first transparent conducting material layer, as compared to applying the second process conditions directly to the underlying functional material; wherein the first transparent conducting material layer functions as a buffer layer to reduce adverse effects for the light transmissible device during formation of said at least one other transparent conducting material layer; wherein the first transparent conducting material layer is an oxygen deficient material layer having limited stability in conductivity in air formed in the presence of a gas mixture comprising oxygen, argon and hydrogen; and wherein the at least one other transparent conducting material layer formed on the first transparent conducting material layer possesses stable conductivity in air for enhancing the conductivity of the electrically conducting structure.

The first deposition power and the first deposition temperature may each be chosen such that adverse temperature and deposition-power induced effects for the light transmissible device are reduced; and wherein the second deposition power may be chosen to provide a desired film quality of said at least one other transparent  
5 conducting material layer.

The structure may further comprise one or more metal layers wherein the first transparent conducting material layer is formed over the metal layers.

Said at least one other transparent conducting material layer formed on the first transparent conducting material layer together may function as an index matching structure for enhancing light output of the device.

5        Said at least one other transparent conducting material formed on the first transparent conducting material layer together may function to improve current spreading of the device.

10        The first transparent conducting material layer and said at least one other transparent conducting material layer may be formed using a physical deposition technique, a chemical deposition technique or both.

15        The first transparent conducting material layer may be formed using direct current (DC) magnetron sputtering.

      The first deposition power may be about 10W power.

20        Said at least one other transparent conducting material layer may be formed using radio frequency (RF) magnetron sputtering.

      The second deposition power may be about 100W power.

25        A substrate temperature during deposition of the first transparent conducting material layer may be about 60°C or less.

      The substrate temperature during deposition of said at least one other transparent conducting material layer may be about 60°C or less.

30        The first transparent conducting material layer and said at least one other transparent conducting material layer may each comprise one or more materials selected from a group consisting of SnO<sub>2</sub>, Ga-In-Sn-O (GITO), Zn-In-Sn-O (ZITO), Ga-In-O (GIO), Zn-In-O (ZIO), In-Sn-O (ITO).

The first transparent conducting material layer and said at least one other transparent conducting material layer may comprise the same transparent conducting material.

In accordance with a second aspect of the present invention, there is provided a method of forming an electrically conducting structure for a light transmissible device, the method comprising, forming a first transparent conducting material layer over underlying functional material using first process conditions, the first process conditions comprise a first deposition power and a first deposition temperature; forming at least one other transparent conducting material layer directly on the first transparent conducting material layer using second process conditions that are different from the first process conditions, the second process conditions comprise a second deposition power and a second deposition temperature; wherein the first process conditions are chosen such that adverse effects to the underlying functional material are reduced during formation of the first transparent conducting material layer, as compared to applying the second process conditions directly to the underlying functional material; wherein the first transparent conducting material layer functions as a buffer layer to reduce adverse effects for the light transmissible device during formation of said at least one other transparent conducting material layer; wherein the first transparent conducting material layer is an oxygen deficient material layer having limited stability in conductivity in air formed in the presence of a gas mixture comprising oxygen, argon and hydrogen; and wherein the at least one other transparent conducting material layer formed on the first transparent conducting material layer possesses stable conductivity in air for enhancing the conductivity of the electrically conducting structure.

The method may comprise choosing each of the first deposition power, the first deposition temperature and the second deposition temperature such that adverse temperature and deposition-power induced effects for the light transmissible device are reduced; and choosing the second deposition power to provide a desired film quality of said at least one other transparent conducting material layer.

The method may further comprise providing one or more metal layers and forming the first transparent conducting material layer over the metal layers.

Said at least one other transparent conducting material layer formed on the first transparent conducting material layer together may function as an index matching structure for enhancing light output of the device.

5            Said at least one other transparent conducting material layer formed on the first transparent conducting material layer together may function to improve current spreading of the device.

10           The first transparent conducting material layer and said at least one other transparent conducting material layer may be formed using a physical deposition technique, a chemical deposition technique or both.

The first transparent conducting material layer may be formed using direct current (DC) magnetron sputtering.

The first deposition power may be about 10W power.

Said at least one other transparent conducting material layer may be formed using radio frequency (RF) magnetron sputtering.

The second deposition power may be about 100W power.

A substrate temperature during deposition of the first transparent conducting material layer may be about 60°C or less.

A substrate temperature during deposition of said at least one other transparent conducting material layer may be about 60°C or less.

The first transparent conducting material layer and said at least one other transparent conducting material layer may each comprise one or more materials selected from a group consisting of SnO<sub>2</sub>, Ga-In-Sn-O (GITO), Zn-In-Sn-O (ZITO), Ga-In-O (GIO), Zn-In-O (ZIO), In-Sn-O (ITO).

The first transparent conducting material layer and said at least one other transparent conducting material layer may comprise the same transparent conducting material.

## BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention will be better understood and readily apparent to one of ordinary skill in the art from the following written description, by way of example only, and in conjunction with the drawings, in which:

Figure 1 is a schematic diagram illustrating a light transmissible device in an example embodiment.

Figure 2 is a schematic diagram illustrating an organic photovoltaic device incorporating an ITO-based electrode of the example embodiment.

Figure 3 shows a graph of integrated light transmittance (%) of the device of Figure 2 vs ITO cathode thickness (nm) and integrated light absorptance (%) of a light absorbing layer of the device of Figure 2 vs ITO cathode thickness (nm).

Figure 4 shows a graph of ITO growth rate (nm/min) vs sputtering power (W) and sheet resistance (ohm/sq) vs sputtering power (W), for films deposited using DC and RF magnetron sputtering.

Figure 5 is a graph of sheet resistance (ohm/sq) vs buffer-ITO<sub>x</sub>/capping-ITO<sub>60-x</sub> thickness for graded-ITO films having different layer combinations.

Figure 6 is a graph of sheet resistance (ohm/sq) vs time (days) for graded-ITO electrodes comprising different layer combinations of buffer-ITO<sub>x</sub>/capping-ITO<sub>60-x</sub> thickness.

Figure 7 is a graph of transmittance (%) vs wavelength (nm) measured for graded-ITO electrodes comprising different layer combinations of buffer-ITO<sub>x</sub>/capping-ITO<sub>60-x</sub> thickness.

Figure 8 is a schematic diagram illustrating a top-emitting organic light emitting diode (OLED) in another example embodiment.

Figure 9 is a graph of current density  $J$  (mA/cm<sup>2</sup>) vs voltage  $V$  (V) measured for a set of top-emitting OLEDs.

Figure 10 is a graph of luminance  $L$  (cd/m<sup>2</sup>) vs voltage  $V$  (V) measured for the set of top-emitting OLEDs.

Figure 11 is a graph of current density  $J$  (mA/cm<sup>2</sup>) vs voltage  $V$  (V).

Figure 12 is a graph of luminance  $L$  ( $\text{cd/m}^2$ ) vs voltage  $V$  (V).

Figure 13 is a graph of luminous efficiency ( $\text{cd/A}$ ) vs current density ( $\text{mA/cm}^2$ ).

5 Figure 14 is a graph of normalised luminance vs operation time (hours).

Figure 15 is a schematic diagram of an organic photovoltaic (OPV) device of another example embodiment.

10 Figure 16 is a graph of incident photon to current efficiency (IPCE) vs wavelength (nm).

Figure 17 is a graph of photocurrent density  $J$  ( $\text{mA/cm}^2$ ) vs voltage  $V$  (V) measured for the device of Figure 15 and a control device under simulated air mass (AM1.5) illumination of about  $100\text{mW/cm}^2$ .

Figure 18 is a schematic diagram illustrating a tandem solar cell in another example embodiment.

20 Figure 19 is a graph of IPCE (%) vs wavelength (nm) for the tandem solar cell.

Figure 20 is a graph of photocurrent density  $J$  ( $\text{mA/cm}^2$ ) vs voltage  $V$  (V) for the tandem solar cell.

25 Figure 21 is a schematic flowchart illustrating a method of forming an electrode structure for a light transmissible device in an example embodiment.

## DETAILED DESCRIPTION

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The example embodiments described herein can provide a transparent electrically conducting graded structure comprising one or more transparent

conducting material. Applications include as an electrode or as a charge recombination interlayer.

Figure 1 is a schematic diagram illustrating a light transmissible device 102 in an example embodiment. The device 102 comprises a substrate 104, a stack 106 of functional layers 108, 110 formed over the substrate 104, a metal layer such as a hole/electron-injector/collector 112 formed over the stack 106 and a transparent graded structure such as a dual or multi-layer TCO-based transparent electrode 114 formed over the hole/electron-injector/collector 112. An encapsulation layer 115 is formed over the electrode 114.

In the description, for illustrative purposes, the electrode 114 comprises two TCO layers. The electrode 114 is a light transmissible structure that is suitable for use in e.g. single junction and tandem structure organic photovoltaic cells, top-emitting and inverted OLEDs and other organic/inorganic functional components that make use of transparent electrode contacts, cover layer(s) or interlayer(s). The electrode 114 comprises an electric conducting TCO buffer layer 116 and an electric conducting TCO capping layer 118. In the example embodiment, the TCO material used is ITO. The substrate 106 can be rigid or flexible and/or opaque or transparent. The functional layers 108, 110 can each comprise organic or inorganic materials. The hole/electron-injector/collector 112 can comprise organic or inorganic materials or a combination of both. The encapsulation layer 115 comprises a suitable material such as  $\text{Al}_2\text{O}_3$ ,  $\text{SiO}_2$ , etc.

It will be appreciated that a transparent graded conducting material layer such as a graded-ITO structure is stable in air and can itself serve as a temporary encapsulation layer. Due to its electric conduction nature, a separate encapsulation layer (see 115) is preferably formed over the transparent graded conducting material layer (see 114). For description purposes, formation of an encapsulation layer is omitted from the following example embodiments.

It has been recognised that TCO has a high work function. Thus on one hand, when the electrode 114 is to be used as an anode, the transparent graded

structure of the electrode 114 can itself function as an anode. On the other hand, if a transparent cathode is to be used for applications in devices such as top-emitting OLEDs, semitransparent PV cells, tandem solar cells etc., a low work function interlayer is desired. The low work function interlayer can comprise low work function metals, organic and inorganic compounds etc. In such cases, the transparent graded structure is used as e.g. a high quality TCO film to cover the low work function interlayer to improve the electrical and optical properties of the cathode system.

In the example embodiment, the transparent graded structure is made up of different "grades" of material. For example, the different "grades" may be formed using different deposition conditions.

In this example embodiment, the buffer layer 116 is formed using direct current (DC) magnetron sputtering at a low power e.g. about 10W. The low power can prevent possible sputtering radiation-induced damage to the underlying layers e.g. 106. It is noted that although the buffer layer 116 formed has a high optical transparency, the buffer layer 116 is porous. The porosity nature gives rise to a limited stability in conductivity.

The capping layer 118 is formed directly over the buffer layer 116 using radio frequency (RF) magnetron sputtering at a high power e.g. about 100W. The capping layer 118 formed has a relatively high density and possesses relatively high optical transparency and stable film conductivity in air. The electrode 114, having the graded structure, is formed as an optically transparent dual-layer ITO electrode that has a relatively high electrical conductivity. It is noted again that the dual-layer structure is an example of a transparent conducting material graded structure. In other words, the graded structure can comprise more than two layers formed using one transparent conducting material or a combination of different transparent conducting materials.

In the example embodiment, an oxidized target with  $\text{In}_2\text{O}_3$  and  $\text{SnO}_2$  in a weight proportion of 9:1 is used for the ITO deposition. The deposition process comprises

applying a less than 0.1% oxygen partial pressure in a gas mixture of oxygen, argon and hydrogen. The ITO deposition rate for the buffer layer 116 is about 2.0 nm/min and for the capping layer 118 is about 4.2 nm/min. The substrate temperature induced during the film deposition is about 60°C. It is noted that the graded-ITO electrode may also  
5 be formed using other physical and chemical deposition methods.

It has been recognised that ITO is an ionically bound semiconducting oxide. Oxygen vacancies are formed relatively easily compared with covalently bound materials. ITO films prepared by DC/RF magnetron sputtering are mainly  
10 nonstoichiometric. The number of the oxygen vacancies is affected by deposition conditions such as sputtering power, substrate temperature, sputtering gas pressure, Sn/In composition in target and the gases in the mixture. Free electrons provided by tin dopants and ionized oxygen vacancy donors comprise the charge carriers for conduction.

Further, the presence of hydrogen in the sputtering gas mixture makes up for oxygen lost in films. When hydrogen is added in the sputtering gas mixture, the grow flux during the magnetron sputtering includes a significant amount of energetic hydrogen species, which can remove weakly bound oxygen in the depositing films. As a  
15 consequence, the addition of hydrogen in the sputtering gas mixture shows a reducing effect on oxide and leads to an increase in the number of oxygen vacancies in the films and hence an increase in the number of charge carriers. As the electrical conductivity is proportionate to the product of charge carrier concentration and the mobility, therefore, the increase in the carrier concentration in the ITO films helps to improve conductivity of  
20 the films in the example embodiment.

For top-emitting OLEDs and organic PV cells, the upper semitransparent cathode structure is crucial. A compound semitransparent cathode comprising ultrathin metal/TCO can be provided using the example embodiment. A compound  
30 semitransparent cathode with an appropriate TCO, e.g., ITO, covering layer can be provided. A good quality graded-TCO layer (see e.g. layer 114) serves as an index matching layer that enhances light output (e.g. enhancing transmittance  $T(\lambda)$ ) in top-emitting or inverted OLEDs and also improves the current spreading due to a relatively

better optical transparency (e.g. having a high  $T(\lambda)$ ) over the visible light wavelengths and due to high electric conductivity. The graded TCO-based transparent electrode 114 in this example embodiment is deposited at low temperatures, is highly conductive, has good stability in film conductivity, has a high deposition rate and can form a good contact  
 5 with the underlying organic/inorganic layers e.g. 112. It has been found that the lowest possible resistivity is achieved in ITO deposited in the presence of hydrogen in the gas mixture at room temperature.

In the example embodiment, a high performance graded ITO structure, in this  
 10 case a dual-layer ITO-cathode, can be provided using a combination of "low-power" and "low-temperature" ITO deposition processes. The buffer layer 116 enables the fabrication of a ITO-based cathode 114 that has high density, high conductivity and high stability with little or no damages to the underlying materials. The combination of the 10 W DC-sputtered buffer-ITO layer 116 and the 100 W RF-sputtered capping-ITO layer  
 15 118 (ie. dual-layer ITO electrode 114) also has a relative high deposition rate and is suitable, but not limited to, applications in organic electronics. The example embodiment can thus provide an effective solution to fabricate TCO-based semitransparent cathodes on surfaces of functional organic and/or inorganic layers at relatively low temperatures.

20 Figure 2 is a schematic diagram illustrating an organic photovoltaic device 202 incorporating an ITO-based electrode 204 of the example embodiment. The device 202 has the following structure: glass/ITO/ Poly(styrene sulfonate)-doped poly(3,4-ethylene dioxothiophene) (PEDOT:PSS)/ poly(3-hexylthiophene) (P3HT): 1-(3-methoxycarbonyl)-propyl-1-phenyl-(6,6)C60 (PCBM) (75nm)/Ca(10nm)/Ag(10nm)/ITO(60nm). In other  
 25 words, the ITO-based electrode 204 has a thickness of about 60nm thick. Table 1 shows the tabulated growth rates for the sputtering processes.

| Process<br>Conditions | DC      |          | RF        |           |
|-----------------------|---------|----------|-----------|-----------|
|                       | 10W     | 100W     | 15W       | 100W      |
| Growth Rate           | 2nm/min | 17nm/min | 0.2nm/min | 4.3nm/min |

Table 1

Figure 3 shows a graph of integrated light transmittance (%) of the device 202 vs ITO cathode thickness (nm) and integrated light absorptance (%) of the P3HT:PCBM layer 206 of the device 202 vs ITO cathode thickness (nm). The maximum transmittance is indicated at numeral 302 while the maximum integrated light absorptance is indicated at numeral 304. Thus, the region of interest of cathode thickness is indicated at numeral 306.

Figure 4 shows a graph of ITO growth rate (nm/min) vs sputtering power (W) and for sheet resistance (ohm/sq) vs sputtering power (W), for films deposited using DC and RF magnetron sputtering. It can be observed that the growth rate of a DC/RF sputtered ITO film increases with the sputtering power and the film resistivity decreases with the power.

In the example embodiment, it has been found that the transmittance  $T(\lambda)$  of the ITO-based electrode 204 can be more than about 85%. Figure 3 represents the wavelength dependent film transmittance. The sheet resistance  $R_s$  (at about 120nm thickness) can be about 25Ω/sq. Further, the ITO-based electrode 204 (Figure 2) has a smooth surface (ie. rms measurements of less than about 1.0nm). The ITO-based electrode 204 (Figure 2) also has less stress and a high etching rate due to its amorphous nature.

It will be appreciated that, unlike bottom-emitting OLEDs that have about 80% of light lost to a wave-guiding mode in a glass substrate, the wave guiding mode in top-emitting OLEDs is suppressed resulting in an increase in light output and therefore, a top-emitting OLED architecture is suitable for OLED-based displays and lighting applications. A high quality upper transparent electrode is beneficial for top-emitting OLEDs. From the optical point of view, an OLED or a top-emitting OLED can be considered as a thin film system. Using the example embodiment, the ITO layer thickness and the compound top cathode structure (see e.g. the graded electrode 114 and the metal layer 112 of Figure 1) can be optimized depending on available emissive materials and the device architecture.

In another example embodiment, the stability of ITO films is investigated. A 60-nm-thick graded ITO structure, in this example, a dual-layer ITO-based upper cathode is deposited on top-emitting OLEDs and semitransparent polymeric PV cells at room temperature. The dual-layer ITO-based cathode has the characteristics of relatively high film deposition-rate, relatively high electric conductivity and relatively high optical transparency with little or no damage to the underlying organic layers.

Figure 5 is a graph of sheet resistance (ohm/sq) vs buffer-ITO<sub>x</sub>/capping-ITO<sub>60-x</sub> thickness for graded-ITO films having different layer combinations. The value x is varied from 0 to 60nm. Buffer-ITO refers to the interlayer ITO buffer layer deposited using DC magnetron sputtering at about 10 W and capping-ITO refers to the ITO capping layer fabricated using RF magnetron sputtering at about 100W in the graded electrode configuration.

It can be seen that the sheet resistance of the 60nm thick graded electrode comprising buffer-ITO<sub>x</sub>/capping-ITO<sub>60-x</sub> films varied from about 67 ohm/sq for buffer-ITO<sub>0</sub>/capping-ITO<sub>60</sub> to about 126 Ohm/sq for buffer-ITO<sub>60</sub>/capping-ITO<sub>0</sub>. Although the buffer-ITO<sub>0</sub>/capping-ITO<sub>60</sub> combination appears to be favourable in terms of film conductivity, the direct use of buffer-ITO<sub>0</sub>/capping-ITO<sub>60</sub> as an upper cathode for top-emitting OLEDs and organic PV cells typically leads to a deterioration of the device performance. This is associated with the possible damage of underlying organic materials due to the use of high sputtering power (e.g. about 100W) during ITO deposition of the capping layer. It is also noted that increasing the thickness of buffer-ITO layer thickness (e.g. to 60nm for buffer-ITO<sub>60</sub>/capping-ITO<sub>0</sub>) is also not favorable. This is because the ITO film (for the buffer layer) prepared by DC magnetron sputtering at about 10 W and at low temperatures, in this case at room temperature, does not have stable film conductivity. This is discussed with reference to Figure 6.

Figure 6 is a graph of sheet resistance (ohm/sq) vs time(days) for graded-ITO electrodes comprising different layer combinations of buffer-ITO<sub>x</sub>/capping-ITO<sub>60-x</sub> thickness. The sheet resistance of 60-nm-thick dual-layer ITO films with different layer combinations of buffer-ITO<sub>0</sub>/capping-ITO<sub>60</sub>, buffer-ITO<sub>15</sub>/capping-ITO<sub>45</sub>, buffer-ITO<sub>30</sub>/capping-ITO<sub>30</sub>, buffer-ITO<sub>45</sub>/capping-ITO<sub>15</sub>, buffer-ITO<sub>60</sub>/capping-ITO<sub>0</sub> measured in

air over a period of 18 days is shown. The results indicate clearly that the conductivity of the buffer-ITO<sub>60</sub>/capping-ITO<sub>0</sub> film (see numeral 602) is not stable in air. Therefore, it is concluded that a single layer ITO deposited by DC magnetron sputtering at low power is not suitable for application as a cathode in organic electronics, although the associated deposition process has the least possible damage to the underlying organic materials. As can be seen in Figure 6, the dual-layer ITO electrodes of buffer-ITO<sub>15</sub>/capping-ITO<sub>45</sub>, buffer-ITO<sub>30</sub>/capping-ITO<sub>30</sub>, and buffer-ITO<sub>45</sub>/capping-ITO<sub>15</sub> may be used for applications in organic electronics due to their characteristics of high film growth-rate and high film stability in air.

Figure 7 is a graph of transmittance (%) vs wavelength (nm) measured for graded-ITO electrodes comprising different layer combinations of buffer-ITO<sub>x</sub>/capping-ITO<sub>60-x</sub> thickness. The wavelength dependent transmittance,  $T(\lambda)$ , of 60-nm-thick dual-layer ITO films of buffer-ITO<sub>0</sub>/capping-ITO<sub>60</sub>, buffer-ITO<sub>15</sub>/capping-ITO<sub>45</sub>, buffer-ITO<sub>30</sub>/capping-ITO<sub>30</sub>, buffer-ITO<sub>45</sub>/capping-ITO<sub>15</sub>, and buffer-ITO<sub>60</sub>/capping-ITO<sub>0</sub> deposited on glass substrates is shown. Apart from a slight deviation in the short wavelength region (ie. below about 400nm for the samples), the  $T(\lambda)$  measured for the dual-layer ITO films have substantially identical light transmittance over the visible light wavelength range. In other words, the results plotted in Figure 7 indicate that the dual-layer ITO-based transparent electrodes of the example embodiment have similar optical properties. Thus, this can provide freedom in optimizing the ITO-based cathode for application in organic electronics.

The dual-layer ITO cathode of the example embodiment can be applied for top-emitting OLEDs and semitransparent organic photovoltaic cells. The high performance dual-layer ITO electrode can improve the lateral conductivity of the electrode. The dual-layer ITO electrode can also function as a refractive index-matching layer to enhance light output in top-emitting OLEDs and total transparency of sub-unit organic PV cells in a PV system, e.g., of semitransparent organic PV cells.

Figure 8 is a schematic diagram illustrating a top-emitting OLED 802 in another example embodiment. The OLED 802 is a tris-(8-hydroxyquinoline) aluminum (Alq<sub>3</sub>)-based top-emitting OLED. The OLED 802 has a structure of structure of glass/ITO/ N,N'-

di(naphthalene-1-yl)-N,N'-diphenylbenzidine (NPB)/ Coumarin 545:Alq<sub>3</sub>/ Alq<sub>3</sub>/LiF/Al/buffer-ITO<sub>45</sub>/capping-ITO<sub>15</sub>, where NPB is a hole transporting layer, Coumarin 545:Alq<sub>3</sub>/ Alq<sub>3</sub> serve as light-emitting and electron transporting layers respectively and LiF/Al/buffer-ITO<sub>45</sub>/capping-ITO<sub>15</sub> is an upper cathode.

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In the example embodiment, a thin film stack of LiF(0.3 nm)/Al(1-5 nm)/buffer-ITO<sub>45</sub>/capping-ITO<sub>15</sub> is used as an upper cathode 804 in the top-emitting OLED 802. The ultra-thin LiF/Al layer at 806 acts as an electron injection contact at the organic/cathode interface at 808. The dual-layer ITO cathode 808 is deposited using DC/RF sputtering using a 6" oxidized ITO target with In<sub>2</sub>O<sub>3</sub> and SnO<sub>2</sub> in a weight ratio of 9:1. The base pressure in the sputter chamber is maintained at less than about 2x10<sup>-4</sup> Pa. The total pressure of the sputtering gas was kept constant at about 3x10<sup>-1</sup> Pa. The deposition process is carried out at room temperature, i.e. the substrate is not heated during and after the film deposition. The combination of buffer-ITO<sub>45</sub>/capping-ITO<sub>15</sub> ITO electrode has a sheet resistance of about 90 Ω/sq (compare Figure 5).

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To confirm that a ITO cathode having a thickness of buffer-ITO<sub>0</sub>/capping-ITO<sub>60</sub> is not suitable for organic electronics, samples comprising LiF(0.3nm)/Al(1.0 nm)/buffer-ITO<sub>0</sub>/capping-ITO<sub>60</sub> layer structures were examined. Results obtained (not shown) showed that OLEDs with a LiF(0.3nm)/Al(1.0 nm)/buffer-ITO<sub>0</sub>/capping-ITO<sub>60</sub> structure as an upper cathode are shorted. This is because the fabrication of the buffer-ITO<sub>0</sub>/capping-ITO<sub>60</sub> electrodes by RF magnetron sputtering at about 100W causes damage to the underlying organic materials. Therefore, the results indicate that a low or no damage buffer-ITO layer is preferred.

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Next, OLEDs having cathode structures of buffer-ITO<sub>45</sub>/capping-ITO<sub>15</sub> and buffer-ITO<sub>60</sub>/capping-ITO<sub>0</sub> are compared.

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Figure 9 is a graph of current density J (mA/cm<sup>2</sup>) vs voltage V (V) measured for a set of top-emitting OLEDs. The OLEDs comprise LiF(0.3 nm)/Al(1.0 nm)/buffer-ITO<sub>45</sub>/capping-ITO<sub>15</sub> and LiF(0.3 nm)/Al(1.0 nm)/buffer-ITO<sub>60</sub>/capping-ITO<sub>0</sub> cathodes in the example embodiment.

Figure 10 is a graph of luminance  $L$  ( $\text{cd/m}^2$ ) vs voltage  $V$  (V) measured for the set of top-emitting OLEDs made with  $\text{LiF}(0.3 \text{ nm})/\text{Al}(1.0 \text{ nm})/\text{buffer-ITO}_{45}/\text{capping-ITO}_{15}$  and  $\text{LiF}(0.3 \text{ nm})/\text{Al}(1.0 \text{ nm})/\text{buffer-ITO}_{60}/\text{capping-ITO}_0$  cathodes in the example embodiment.

5 From Figures 9 and 10, the top-emitting OLEDs with the two types of upper cathode structures have similar J-V and L-V characteristics. However, with reference to Figures 5 and 6, the graded electrode comprising the  $\text{buffer-ITO}_{45}/\text{capping-ITO}_{15}$  structure is a more superior choice to that of comprising the  $\text{buffer-ITO}_{60}/\text{capping-ITO}_0$  structure, as an upper transparent electrode for device applications, since the electrical  
10 conductivity of the  $\text{buffer-ITO}_{45}/\text{capping-ITO}_{15}$  structure is higher and is also stable as compared to those properties of the  $\text{ITO}_{60}/\text{capping-ITO}_0$  ITO structure.

To investigate the performance of the dual-layer electrode of the example embodiments against an ITO electrode without a buffer layer, it is noted that, generally,  
15 an increase in the metal (e.g. aluminum) interlayer thickness may suppress the subsequent sputtering-induced damage to the organic layers. However, it will be appreciated that a thick metal interlayer typically causes a reduction in light output from the upper electrode side due to increased internal reflection.

20 In another example embodiment, a  $\text{LiF}(0.3 \text{ nm})/\text{Al}/\text{buffer-ITO}_0/\text{capping-ITO}_{60}$  structure is found to be able to function as an upper cathode in top-emitting OLEDs with an aluminum layer thickness of more than 5.0 nm. Top-emitting OLEDs comprising a  $\text{LiF}(0.3 \text{ nm})/\text{Al}(5.0 \text{ nm})/\text{buffer-ITO}_0/\text{capping-ITO}_{60}$  cathode structure and top-emitting OLEDs comprising a  $\text{LiF}(0.3 \text{ nm})/\text{Al}(5.0 \text{ nm})/\text{buffer-ITO}_{45}/\text{capping-ITO}_{15}$  cathode  
25 structure are compared in the example embodiment.

Figure 11 is a graph of current density  $J$  ( $\text{mA/cm}^2$ ) vs voltage  $V$  (V). Figure 12 is a graph of luminance  $L$  ( $\text{cd/m}^2$ ) vs voltage  $V$  (V). From Figures 11 and 12, it is observed that the top-emitting OLEDs made with  $\text{LiF}(0.3 \text{ nm})/\text{Al}(5.0 \text{ nm})/\text{buffer-ITO}_0/\text{capping-ITO}_{60}$   
30 and  $\text{LiF}(0.3 \text{ nm})/\text{Al}(5.0 \text{ nm})/\text{buffer-ITO}_{45}/\text{capping-ITO}_{15}$  structures have similar or comparable J-V and L-J characteristics.

Figure 13 is a graph of luminous efficiency (cd/A) vs current density (mA/cm<sup>2</sup>).  
Figure 14 is a graph of normalised luminance vs operation time (hours).

It is observed that the OLEDs comprising the LiF(0.3 nm)/Al(5.0 nm)/buffer-  
5 ITO<sub>0</sub>/capping-ITO<sub>60</sub> structures have a lower luminous efficiency (see numeral 1302) and  
are less stable in luminance over time (see numeral 1402) as compared to the  
structurally identical top-emitting OLEDs fabricated with LiF(0.3 nm)/Al(5.0 nm)/buffer-  
ITO<sub>45</sub>/capping-ITO<sub>15</sub> structures (see numerals 1304 and 1404). The difference in  
10 performance can be attributed to partial damage to the underlying organic materials  
which is induced due to the fabrication of buffer-ITO<sub>0</sub>/capping-ITO<sub>60</sub> by RF magnetron  
sputtering at about 100 W.

Thus, in the example embodiments, it has been demonstrated that the graded  
ITO cathode, e.g. comprising a buffer-ITO<sub>45</sub>/capping-ITO<sub>15</sub> structure, is suitable for  
15 applications in top-emitting OLEDs.

After describing the above example embodiments with respect to OLEDs,  
photovoltaic (PV) cells are discussed in the following description.

20 Thin film organic PV cells may provide low-cost power generation. Organic  
semiconductors, functioning as active components in PV devices, have advantages  
including in terms of large surface area, cost effectiveness, chemical tenability and  
mechanical flexibility. It is noted that limited absorption of the sun spectrum and a  
relatively low open circuit voltage are two factors that can limit the efficiency of current  
25 organic PV cells. Therefore, in addition to searching for suitable low band gap organic  
semiconducting materials for photovoltaic applications, it has been recognised that one  
way to improve the performance of organic PV cells is to use tandem structures. The  
tandem PV cells can be formed by stacking the sub-cells using semitransparent  
cathodes. It is also desired to have high performance semitransparent cathodes in  
30 organic PV cells.

Figure 15 is a schematic diagram of an organic photovoltaic (PV) device 1502 of  
another example embodiment. The device 1502 is a semipolymer PV cell and has the

following structure: glass/ITO/ Poly(styrene sulfonate)-doped poly(3,4-ethylene dioxythiophene) (PEDOT:PSS) (40nm)/ poly(3-hexylthiophene) (P3HT): 1-(3-methoxycarbonyl)-propyl-1-phenyl-(6,6)C60 (PCBM)(75 nm)/Ca(10nm)/Ag(10nm)/ buffer-ITO<sub>45</sub>/capping-ITO<sub>15</sub>. Thus, the device 1502 comprises a buffer-ITO<sub>45</sub>/capping-ITO<sub>15</sub> structure 1504 as part of an upper transparent electrode.

In order to study the effect of the dual-layer ITO structure 1504 on the performance of the device 1502, a control device (not shown) having a device configuration of glass/ITO/PEDOT-PSS (40nm)/P3HT:PCBM(75 nm)/Ca (10nm)/Ag(100nm) is fabricated. It is noted that this control device has an electrode comprising Ag of a thickness of about 100nm instead of the buffer-ITO<sub>45</sub>/capping-ITO<sub>15</sub> structure 1504.

Figure 16 is a graph of incident photon to current efficiency (IPCE) vs wavelength (nm). Plot 1602 shows the performance of the device 1502 and plot 1604 shows the performance of the control device.

Figure 17 is a graph of photocurrent density  $J$  (mA/cm<sup>2</sup>) vs voltage  $V$  (V) measured for the device 1502 and the control device under simulated air mass (AM1.5) illumination of about 100mW/cm<sup>2</sup>. Plot 1702 shows the J-V characteristics of the device 1502 in "the dark" conditions while plot 1704 shows the J-V characteristics of the device 1502 in AM 1.5 conditions. Plot 1706 shows the J-V characteristics of the control device in "the dark" conditions while plot 1708 shows the J-V characteristics of the control device in AM 1.5 conditions.

Table 2 below tabulates the performances of the control device and the PV device 1502.

| Sample                          | IPCE% | V <sub>oc</sub> (V) | J <sub>sc</sub> (mA/cm <sup>2</sup> ) | FF% | PCE % |
|---------------------------------|-------|---------------------|---------------------------------------|-----|-------|
| Semitransparent polymer PV cell | 48    | 0.50                | 5.80                                  | 42  | 1.23  |
| Control polymer PV cell         | 59    | 0.57                | 8.22                                  | 43  | 2.02  |

Table 2

FF is the fill factor and PCE is the power conversion efficiency.

As can be seen from the table, the PV device 1502 demonstrates an external quantum efficiency of about 48% and a conversion efficiency of about 1.23%. The semitransparent PV cell or device 1502 yields a comparable FF, but a relatively lower short circuit current density ( $J_{sc}$ ) of about  $5.8 \text{ mA/cm}^2$ , in comparison with that of about  $8.22 \text{ mA/cm}^2$  measured for the control device, as shown in Table 2. The slight decrease in photocurrent density in the semitransparent polymer PV cell or device 1502 is expected as more than 40% of the incident light (compare Fig.3) is transmitted through the top graded TCO electrode or structure 1504.

After describing the above example embodiments with respect to PV cells, tandem organic solar cells are discussed in the following description.

In tandem organic solar cells, each single solar cell can be made very thin (about 20-40 nm). This has advantages for charge transport including the following. The open circuit voltage of a tandem PV cell can be increased. Tandem organic PV cells can fully utilize the solar spectrum by stacking 2 or more different solar cells that respond to different parts of the solar spectrum.

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In another example embodiment, a high performance graded transparent conducting material structure such as a graded structure of a buffer-ITO/capping-ITO type is used as a charge recombination interlayer in thin film tandem solar cells.

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Applications of the transparent conducting material graded structure of the example embodiments include as an anode, a cathode and/or as a charge recombination zone in tandem solar cells or any other functional organic/inorganic devices that make use of an optically transparent and electrically conductivity layer.

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Figure 18 is a schematic diagram illustrating a tandem solar cell in the example embodiment. The tandem solar cell 1802 has the following structure: ITO/PEDOT:PSS/P3HT:PCBM(75nm)/Ca(5nm)/Ag(5nm)/buffer-ITO45/capping-ITO15

/PEDOT:PSS/P3HT:PCBM(200nm)/Ca(20nm)/Ag(200nm). Thus, the tandem solar cell 1802 comprises a graded TCO interlayer 1804 of buffer-ITO/capping-ITO for charge recombination.

5           Figure 19 is a graph of IPCE (%) vs wavelength (nm) for the tandem solar cell 1802. Figure 20 is a graph of photocurrent density J (mA/cm<sup>2</sup>) vs voltage V (V) for the tandem solar cell 1802.

Table 3 below tabulates the performances of the tandem solar cell 1802.

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| Sample             | IPCE% | V <sub>oc</sub> (V) | J <sub>sc</sub> (mA/cm <sup>2</sup> ) | FF% | PCE% |
|--------------------|-------|---------------------|---------------------------------------|-----|------|
| Tandem<br>OPV cell | 29.11 | 0.80                | 4.60                                  | 42  | 1.56 |

Table 3

Thus, the primary results of the tandem polymer PV cell 1802 shows an enhanced open circuit (V<sub>oc</sub>) voltage of about 0.8V, in comparison with that of about 0.5 V measured for single junction semitransparent PV cell see e.g. device 1502 of Figure 5.

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Figure 21 is a schematic flowchart 2100 illustrating a method of forming an electrically conducting structure for a light transmissible device in an example embodiment. At step 2102, a first transparent conducting material layer is formed using first process conditions. At step 2104, at least one other transparent  
20   conducting material layer is formed directly on the first layer using second process conditions that are different from the first process conditions. At step 2106, the first layer functions as a buffer layer to reduce adverse effects for the light transmissible device during formation of said at least one other transparent conducting material layer.

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In the above example embodiments, an organic and/or inorganic device can be provided that comprises a rigid or flexible opaque or transparent substrate base, a stack of inorganic and/or organic functional layers formed over the said substrate, an organic or inorganic hole/electron-injector/collector formed over the stack of inorganic and/or

organic functional layers, a dual- or multi-layer TCO based transparent electrode formed over the organic or inorganic hole/electron-injector/collector and an encapsulation layer.

The transparent substrate can be glass or clear plastic foils with permeation barrier layers that are suitable for OLED/polymer OLED (PLED) applications. The opaque substrate can be a non-transparent inorganic and organic substrate that can be a bare substrate or the surface of the functional organic and inorganic materials. The dual- or multi-layer TCO materials can be made by solution and vacuum methods at a room process temperature or above.

The graded-TCO based transparent electrode can form an electric conductivity and an optical coupling layer, depending on the applications. The TCO-based electrode can comprise a buffer layer to prevent possible damage to the underlying functional layers. The transparent electrode material is selected from oxygen deficient TCOs formed by solution or vacuum film fabrication methods. The materials can be selected from a group comprising indium tin oxide (ITO), zinc aluminum oxide, indium zinc oxide, tin oxide, Ga-In-Sn-O (GITO), Zn-In-Sn-O (ZITO), Ga-In-O (GIO), Zn-In-O (ZIO), and other materials suitable for use as transparent or semitransparent electrode in organic and/or inorganic devices. These materials can be used individually or with a combination of different materials.

The thickness of the TCO layers can be adjusted. The electron injector may be formed of a low work-function metal or metal alloy. The low work-function metals and metal alloys are selected from a group comprising Ca, Li, Ba, Mg. The electron injector may be formed of a thin bilayer of LiF/Al or CsF/Al or Mg/Ag or Ca/Ag.

The above described example embodiments can provide a buffer-ITO<sub>45</sub>/capping-ITO<sub>15</sub> dual-layer ITO structure for inverted OLEDs, top-emitting OLEDs, semitransparent polymer photovoltaic (PV) cells, tandem structure PV cells, and functional components comprising a stack of inorganic/organic diodes, transistors or devices that make use of transparent conducting layer(s). The inventors have recognised that the TCO-based semitransparent cathode can be further optimized in order to enhance light harvesting in

the photoactive layer as well as the transmission of sub-unit solar cells in tandem structure thin film photovoltaic devices.

The graded-TCO electrode of the example embodiments can be used as a transparent contact or a transparent conductive electrode in emissive and non-emissive flat panel displays, organic, inorganic and hybrid photovoltaics, sensors, heat mirrors, electric shielding, transparent diodes, transistors, circuits and other optoelectronic applications. It can also be used in memory devices, TCO-based p-n junctions, electric contacts, transparent circuits, OLED/Polymer LED (PLED) displays, automobile indication instrument/displays, outdoor instrument displays, signage or advertisement display boards, PC and TV monitors for outdoors and in organic electronics including flexible OLED (FOLED), organic thin film transistors (OTFTs) etc.

The above example embodiments can provide a high quality TCO-based electrode with smooth surfaces, high electric conductivity, high optical transparency and with substantially no damage to underlying organic materials at low processing temperatures. In addition to transparency and conductivity, the example embodiments can offer other advantages such as not requiring addition of new deposition facilities and not requiring pre- or post annealing. The example embodiments can also be suitable for use for large area rigid and flexible substrates.

The example embodiments can lead to obtaining a tandem OPV cell that has an increased  $V_{oc}$ , a thinner active layer for better charge transport properties and having a broad spectral response in the solar spectrum. The example embodiments can also lead to obtaining a TOLED or a semitransparent OPV cell that has high electrical conductivity and optical transparency e.g. via index matching and current spreading, that has a smooth surface to reduce the electric shorts, that has a high deposition rate with no damage to the underlying layers, is stable in air and that can be produced in a scaleable and low-cost process.

In the above example embodiments, graded-ITO film is used because of its preferred properties of high electric conductivity and optical transparency over the visible light wavelength region. Magnetron sputtering is described as the technique for

depositing ITO because this technique has the advantage of fabricating uniform ITO films reproducibly. Both reactive and non-reactive forms of DC/RF magnetron sputtering can be used for film preparation. Magnetron sputtering also appears to be able to produce high quality ITO films. Further, it will be appreciated that ITO films can also be prepared by other techniques including but not limited to thermal evaporation deposition, electron beam evaporation, spray pyrolysis, chemical vapor deposition, dip-coating techniques, pulsed laser deposition (PLD) method, unbalanced magnetron sputtering and various physical and chemical deposition methods. It will be appreciated that these deposition methods, similar to the magnetron sputtering technique described in the example embodiments, have process conditions that can be controlled/chosen such that adverse deposition induced effects for the light transmissible device are reduced using a first transparent conducting material layer and such that a desired film quality for the light transmissible device can be provided in at least one other transparent conducting material layer, of an electrically conducting structure for a light transmissible device. These process conditions include, but are not limited to, temperature and deposition power.

The described example embodiments can have fabrication flexibility such as using a single deposition process or a combination of different fabrication technologies.

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Furthermore, it will be appreciated that the described example embodiments are not limited to using ITO but can include other oxide materials, including  $\text{SnO}_2$ , Ga-In-Sn-O (GITO), Zn-In-Sn-O (ZITO), Ga-In-O (GIO), Zn-In-O (ZIO) and other transparent conducting materials suitable for organic electronics. They can also include using conducting polymers/organics, transparent conducting nitrides and other transparent conducting materials. These materials can be used individually or with a combination of different materials.

It will be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

30

**CLAIMS**

1. An electrically conducting structure for a light transmissible device, the structure comprising,

a first transparent conducting material layer formed over underlying functional material using first process conditions, the first process conditions comprise a first deposition power and a first deposition temperature;

at least one other transparent conducting material layer formed directly on the first transparent conducting material layer, said at least one other transparent conducting material layer being formed using second process conditions that are different from the first process conditions, the second process conditions comprise a second deposition power and a second deposition temperature;

wherein the first process conditions are chosen such that adverse effects to the underlying functional material are reduced during formation of the first transparent conducting material layer, as compared to applying the second process conditions directly to the underlying functional material;

wherein the first transparent conducting material layer functions as a buffer layer to reduce adverse effects for the light transmissible device during formation of said at least one other transparent conducting material layer;

wherein the first transparent conducting material layer is an oxygen deficient material layer having limited stability in conductivity in air formed in the presence of a gas mixture comprising oxygen, argon and hydrogen; and

wherein the at least one other transparent conducting material layer formed on the first transparent conducting material layer possesses stable conductivity in air for enhancing the conductivity of the electrically conducting structure.

2. The structure as claimed in claim 1,

wherein the first deposition power, the first deposition temperature and the second deposition temperature are each chosen such that adverse temperature and deposition-power induced effects for the light transmissible device are reduced; and

5        wherein the second deposition power is chosen to provide a desired film quality of said at least one other transparent conducting material layer.

3.        The structure as claimed in claims 1 or 2, further comprising one or more metal layers wherein the first transparent conducting material layer is formed  
10        over the metal layers.

4. The structure as claimed in any one of claims 1 to 3, wherein said at least one other transparent conducting material layer formed on the first transparent conducting material layer together function as an index matching structure for enhancing light output of the device.

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5. The structure as claimed in any one of the preceding claims, wherein said at least one other transparent conducting material formed on the first transparent conducting material layer together function to improve current spreading of the device.

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6. The structure as claimed in any one of the preceding claims, wherein the first transparent conducting material layer and said at least one other transparent conducting material layer are formed using a physical deposition technique, a chemical deposition technique or both.

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7. The structure as claimed in claim 6, wherein the first transparent conducting material layer is formed using direct current (DC) magnetron sputtering.

8. The structure as claimed in any one of the preceding claims, wherein the first deposition power is about 10W power.

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9. The structure as claimed in any one of claims 6 to 8, wherein said at least one other transparent conducting material layer is formed using radio frequency (RF) magnetron sputtering.

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10. The structure as claimed in any one of the preceding claims, wherein the second deposition power is about 100W power.

11. The structure as claimed in any one of the preceding claims, wherein a substrate temperature during deposition of the first transparent conducting material layer is about 60°C or less.

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12. The structure as claimed in any one of the preceding claims, wherein the substrate temperature during deposition of said at least one other transparent conducting material layer is about 60°C or less.

13. The structure as claimed in any one of the preceding claims, wherein the first transparent conducting material layer and said at least one other transparent conducting material layer each comprises one or more materials selected from a group consisting of  $\text{SnO}_2$ , Ga-In-Sn-O (GITO), Zn-In-Sn-O (ZITO), Ga-In-O (GIO), Zn-In-O (ZIO), and In-Sn-O (ITO).

14. The structure as claimed in claim 13, wherein the first layer and said at least one other transparent conducting material layer comprise the same transparent conducting material.

15. A method of forming an electrically conducting structure for a light transmissible device, the method comprising,

forming a first transparent conducting material layer over underlying functional material using first process conditions, the first process conditions comprise a first deposition power and a first deposition temperature;

forming at least one other transparent conducting material layer directly on the first transparent conducting material layer using second process conditions that are different from the first process conditions, the second process conditions comprise a second deposition power and a second deposition temperature;

wherein the first process conditions are chosen such that adverse effects to the underlying functional material are reduced during formation of the first transparent conducting material layer, as compared to applying the second process conditions directly to the underlying functional material;

wherein the first transparent conducting material layer functions as a buffer layer to reduce adverse effects for the light transmissible device during formation of said at least one other transparent conducting material layer;

wherein the first transparent conducting material layer is an oxygen deficient material layer having limited stability in conductivity in air formed in the presence of a gas mixture comprising oxygen, argon and hydrogen; and

wherein the at least one other transparent conducting material layer formed on the first transparent conducting material layer possesses stable conductivity in air for enhancing the conductivity of the electrically conducting structure.

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16. The method as claimed in claim 15, further comprising,  
choosing each of the first deposition power, the first deposition  
temperature and the second deposition temperature such that adverse

temperature and deposition-power induced effects for the light transmissible device are reduced; and

choosing the second deposition power to provide a desired film quality of said at least one other transparent conducting material layer.

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17. The method as claimed in claims 15 or 16, further comprising providing one or more metal layers and forming the first transparent conducting material layer over the metal layers.

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18. The method as claimed in any one of claims 15 to 17, wherein said at least one other transparent conducting material layer formed on the first transparent conducting material layer together function as an index matching structure for enhancing light output of the device.

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19. The method as claimed in any one of claims 15 to 18, wherein said at least one other transparent conducting material layer formed on the first transparent conducting material layer together function to improve current spreading of the device.

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20. The method as claimed in any one of claims 15 to 19, wherein the first transparent conducting material layer and said at least one other transparent conducting material layer are formed using a physical deposition technique, a chemical deposition technique or both.

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21. The method as claimed in claim 20, wherein the first transparent conducting material layer is formed using direct current (DC) magnetron sputtering.

22. The method as claimed in any one of claims 15 to 21, wherein the first deposition power is about 10W power.

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23. The method as claimed in any one of claims 20 to 22, wherein said at least one other transparent conducting material layer is formed using radio frequency (RF) magnetron sputtering.

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24. The method as claimed in any one of claims 15 to 23, wherein the second deposition power is about 100W power.

25. The method as claimed in any one of claims 15 to 24, wherein a substrate temperature during deposition of the first transparent conducting material layer is about 60°C or less.

5           26. The method as claimed in any one of claims 15 to 25, wherein a substrate temperature during deposition of said at least one other transparent conducting material layer is about 60°C or less.

10           27. The method as claimed in any one of claims 15 to 26, wherein the first transparent conducting material layer and said at least one other transparent conducting material layer each comprises one or more materials selected from a group consisting of SnO<sub>2</sub>, Ga-In-Sn-O (GITO), Zn-In-Sn-O (ZITO), Ga-In-O (GIO), Zn-In-O (ZIO), and In-Sn-O (ITO).

15           28. The method as claimed in claim 27, wherein the first transparent conducting material layer and said at least one other transparent conducting material layer comprise the same transparent conducting material.