

ALUMINUM-DOPED ZINC OXIDE FILM AND METHOD OF FORMING THE SAME**CROSS-REFERENCE TO RELATED APPLICATION**

[0001] This application claims the benefit of priority of Singapore application No. 10201701304Q filed on February 17, 2017, the contents of it being hereby incorporated by reference in its entirety for all purposes.

TECHNICAL FIELD

[0002] Various aspects of this disclosure relate to an aluminum-doped zinc oxide film. Various aspects of this disclosure relate to a method of forming an aluminum-doped zinc oxide film.

BACKGROUND

[0003] The demand for transparent conductive films (TCF) and glass is set to rapidly rise between 2014 and 2024. FIG. 1A is a plot of market size (in millions of United States Dollars (USD)) as a function of year showing the predicted market share for different transparent conductive films. This market growth is predominantly fueled by the rise of portable devices, and the penetration of touch in traditional displays applications such as notebooks and monitors. FIG. 1B shows a schematic of the operation of a touch screen. FIG. 1C shows a schematic illustrating the structure of a touch screen. The touch screen may include an optional bottom shield (not shown), a glass, a conductive coating (aluminum tin oxide (ATO), indium tin oxide (ITO), or tin oxide (TO)) on the glass, an electrode pattern on the conductive coating, a hard coat with anti-glare (AG) on the electrode pattern, and a top coat on the hard coat. The composition of the mobile phone market is being transformed with smart phones, which has been predicted to increase its market share from 55% to 74% between 2013 and 2023. This translates into new opportunities for touch screen suppliers.

[0004] The supply of such indium tin oxide (ITO) layers is limited, and most suppliers are unwilling to switch production capacity given the absence of volume demand. FIG. 1D is a plot of the price of indium (in United States Dollars per kilogram or USD/kg) as a function of year illustrating the price of indium over recent years. The price of primary indium has increased from 200 USD per kilogram in 2004 to 1000 USD per kilogram in 2006. This translates into much

higher prices than those found in the touch screen market. FIG. 1E is a schematic showing forming of an indium tin oxide (ITO) layer on a plastic substrate by sputtering.

[0005] The compound annual growth rate (CAGR) would be 20% initially, but is expected to slow down to 2-3% near 2023. Nowadays, plasma based (magnetron-sputtering), pulsed laser deposition (PLD), atomic layer deposition (ALD) or chemical vapor deposition (CVD) methods are employed on industrial scale to obtain high quality aluminum zinc oxide (AZO) thin films with resistivity of 10^{-3} – 10^{-4} Ω cm and visible transparency > 90%, although instrumental complexity poses high investment costs as well as limits scalability. FIG. 1F shows a table indicating the various properties of aluminum zinc oxide (AZO) films formed by various deposition techniques. Various techniques may involve high temperature processes above 200°, may involve high vacuum or high cost equipment, may involve complex processes, may have high process costs, and/or may not be suitable for flexible substrates.

[0006] As such, low cost non-vacuum methods for AZO thin films are of immense interest. AZO films may have applications in touch screens in smartphones, tablets and monitors. The sheet resistance may be required to be high (at about 100-200 ohms /square). The transmittance may also be required to be around 90%, although this may vary slightly depending on the application.

SUMMARY

[0007] Various embodiments may provide a method of forming an aluminum-doped zinc oxide film. The method may include forming a seed layer on a substrate by a solution deposition process. The method may also include depositing a precursor solution including zinc nitrate and ammonium hydroxide on the seed layer. The method may further include contacting the precursor solution with aluminum metal at a temperature equal to or less than 85 °C. The aluminum-doped zinc oxide film may be formed from the precursor solution and the aluminum metal.

[0008] Various embodiments may relate to an aluminum-doped zinc oxide film formed by a method as described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] The invention will be better understood with reference to the detailed description when considered in conjunction with the non-limiting examples and the accompanying drawings, in which:

FIG. 1A is a plot of market size (in millions of United States Dollars (USD)) as a function of year showing the predicted market share for different transparent conductive films.

FIG. 1B shows a schematic of the operation of a touch screen.

FIG. 1C shows a schematic illustrating the structure of a touch screen.

FIG. 1D is a plot of the price of indium (in United States Dollars per kilogram or USD/kg) as a function of year illustrating the price of indium over recent years.

FIG. 1E is a schematic showing forming of an indium tin oxide (ITO) layer on a plastic substrate by sputtering.

FIG. 1F shows a table indicating the various properties of aluminum zinc oxide (AZO) films formed by various deposition techniques.

FIG. 2 is a schematic illustrating a method of forming an aluminum-doped zinc oxide film according to various embodiments.

FIG. 3 is a schematic illustrating a method of forming an aluminum-doped zinc oxide film according to various embodiments.

FIG. 4 is a plot of transmittance (in percent or %) as a function of wavelength (in nanometers or nm) showing the transmittance on films formed from a zinc oxide (ZnO) seed layer and an aluminum-doped zinc oxide (AZO) seed layer according to various embodiments.

FIG. 5A is a scanning electron microscopy (SEM) image showing a top planar view of an aluminum-doped zinc oxide film grown using a zinc oxide (ZnO) seed layer according to various embodiments.

FIG. 5B is another scanning electron microscopy (SEM) image showing a cross sectional side view of the aluminum-doped zinc oxide film shown in FIG. 5A according to various embodiments.

FIG. 5C is a scanning electron microscopy (SEM) image showing a top planar view of an aluminum-doped zinc oxide film grown using an aluminum-doped zinc oxide (AZO) seed layer according to various embodiments.

FIG. 5D is another scanning electron microscopy (SEM) image showing a cross sectional side view of the aluminum-doped zinc oxide film shown in FIG. 5C according to various embodiments.

FIG. 6A is a scanning electron microscopy (SEM) image showing a top planar view of an aluminum-doped zinc oxide film grown using an aluminum-doped zinc oxide (AZO) seed layer and an original bath recipe according to various embodiments.

FIG. 6B is a scanning electron microscopy (SEM) image showing a top planar view of an aluminum-doped zinc oxide film grown using a zinc oxide (ZnO) seed layer and an original bath recipe according to various embodiments.

FIG. 6C is a scanning electron microscopy (SEM) image showing a top planar view of an aluminum-doped zinc oxide film grown using an aluminum-doped zinc oxide (AZO) seed layer and a 50 : 50 bath recipe according to various embodiments.

FIG. 6D is a scanning electron microscopy (SEM) image showing a top planar view of an aluminum-doped zinc oxide film grown using a zinc oxide (ZnO) seed layer and a 50 : 50 bath recipe according to various embodiments.

FIG. 7 is a table comparing the sheet resistances (in ohms per square or $\Omega/\square$) of a aluminum-doped zinc oxide film grown using an aluminum-doped zinc oxide (AZO) seed layer and an aluminum-doped zinc oxide film grown using a zinc oxide (ZnO) seed layer according to various embodiments.

FIG. 8 is a plot of transmittance T (in percent or %) as a function of wavelengths (in nanometers or nm) showing the transmittance of aluminum-doped zinc oxide films according to various embodiments as well as the transmittance of conventional glasses.

FIG. 9 is a table comparing the sheet resistance (in ohms/square (sq)) and transmittance (in percent or %) of various aluminum-doped zinc oxide films grown over various substrates.

FIG. 10 shows an optical image of a glass having a first portion coated with a film according to various embodiments and a second portion uncoated.

FIG. 11 shows images of a potential application of a film according to various embodiments.

DETAILED DESCRIPTION

[0010] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and structural, and logical changes may be

made without departing from the scope of the invention. The various embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

[0011] Embodiments described in the context of one of the methods or film are analogously valid for the other methods or films. Similarly, embodiments described in the context of a method are analogously valid for film, and vice versa.

[0012] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0013] The word "over" used with regards to a deposited material formed "over" a side or surface, may be used herein to mean that the deposited material may be formed "directly on", e.g. in direct contact with, the implied side or surface. The word "over" used with regards to a deposited material formed "over" a side or surface, may also be used herein to mean that the deposited material may be formed "indirectly on" the implied side or surface with one or more additional layers being arranged between the implied side or surface and the deposited material. In other words, a first layer "over" a second layer may refer to the first layer directly on the second layer, or that the first layer and the second layer are separated by one or more intervening layers.

[0014] The film as described herein may be operable in various orientations, and thus it should be understood that the terms "top", "topmost", "bottom", "bottommost" etc., when used in the following description are used for convenience and to aid understanding of relative positions or directions, and not intended to limit the orientation of the film.

[0015] In the context of various embodiments, the articles "a", "an" and "the" as used with regard to a feature or element include a reference to one or more of the features or elements.

[0016] In the context of various embodiments, the term "about" or "approximately" as applied to a numeric value encompasses the exact value and a reasonable variance.

[0017] As used herein, the term "and/or" includes any and all combinations of one or more of the associated listed items.

[0018] Various embodiments may relate to a method of fabricating conductive AZO thin films (also referred to as an aluminum-doped zinc oxide film) with aqueous solution deposition. Various embodiments may relate to a formulation for a growth solution suitable or compatible with aluminum zinc oxide (AZO) and zinc oxide (ZnO) seed layer.

[0019] Controlling the doping dynamics during thin film growth may involve using a source of metal aluminum (which may be of a predetermined purity) immersed in the alkaline aqueous precursor solution. After combining with ultraviolet (UV) radiation treatment, high quality AZO thin films may be obtained without exceeding temperatures of 85 ° C at any process step. Deposition of large-area AZO on a temperature sensitive- and non-conducting substrate, such as a flexible polymer or plastic substrate may be possible.

[0020] FIG. 2 is a schematic illustrating a method of forming an aluminum-doped zinc oxide film according to various embodiments. The method may include, in 202, forming a seed layer on a substrate by a solution deposition process. The method may also include, in 204, depositing a precursor solution including zinc nitrate and ammonium hydroxide on the seed layer. The method may further include, in 206, contacting the precursor solution with aluminum metal at a temperature equal to or less than 85 °C. The aluminum-doped zinc oxide film may be formed from or based on the precursor solution and the aluminum metal.

[0021] In other words, the method may include forming a seed layer, and depositing a precursor solution on the seed layer. An aluminum metal may be dipped or immersed into a precursor solution to form the aluminum-doped zinc oxide film. The temperature of the process may not exceed 85 °C.

[0022] Various embodiments may seek to address problems faced by conventional methods of forming transparent conductive films. Various embodiments may have advantages over conventional methods. Various embodiments may form a film which have advantages over films formed by conventional methods.

[0023] Various embodiments may reduce the number of processing steps, decrease material and/or process costs. Various embodiments may use commercial chemical materials that are low cost and commercially available. Various embodiments may involve growth in a formula solution, and in a non-vacuum environment. Various embodiments may have no high energy requirements,

and may result in energy savings. Various embodiments may increase productivity and product yield rate.

[0024] For avoidance of doubt, the steps shown in FIG. 2 may not necessary be in sequence. For instance, in various embodiments, step 206 may occur after step 204, or may occur simultaneously with 204, or may occur before step 204.

[0025] Various embodiments may involve a whole process temperature equal to or less than 85°. The deposition of the precursor solution on the seed layer may also occur at a temperature at equal to or less than 85 °C

[0026] Various embodiments may form a film with increased performance. Various embodiments may allow forming or fabricating a film on a plastic substrate or film, resulting in a flexible transparent conductive film (TCF). Various embodiments may provide an easy coating on a large area substrate.

[0027] Aluminum-doped zinc oxide may alternatively be referred to as aluminum zinc oxide (AZO).

[0028] In various embodiments, the seed layer may include zinc oxide (ZnO). Forming the seed layer (using the solution deposition process) may include depositing a dispersion including zinc oxide nanoparticles or nanostructures on the substrate. The dispersion may also include an aqueous solution such as ammonium hydroxide (NH₄OH). The zinc oxide nanoparticles or nanostructures may be suspended over the aqueous solution. The method may also include heating the deposited zinc oxide nanoparticles or nanostructures to form the seed layer. Depositing the dispersion on the substrate may include spin coating or dip coating the substrate with the dispersion.

[0029] In various other embodiments, the seed layer may include aluminum-doped zinc oxide (AZO). Forming the seed layer (using the solution deposition process) may include depositing a dispersion including AZO nanoparticles or nanostructures on the substrate. The dispersion may also include an aqueous solution such as ammonium hydroxide (NH₄OH). The AZO nanoparticles or nanostructures may be suspended over the aqueous solution. The method may also include heating the deposited AZO nanoparticles or nanostructure to form the seed layer. Depositing the dispersion on the substrate may include spin coating or dip coating the substrate with the dispersion.

[0030] The method may also include heating the deposited dispersion to form the seed layer. Heating the deposited dispersion may include heating on a hotplate. Heating the deposited dispersion may remove the aqueous solution. The seed layer may include a plurality of nanostructures such as nanorods.

[0031] In various embodiments, the method may include forming a mixture including zinc oxide, zinc nitrate and ammonium hydroxide by mixing ammonium citrate, ammonium nitrate and zinc oxide powder. The zinc oxide may be insoluble and may be suspended over a solution of zinc nitrate and ammonium hydroxide.

[0032] The method may further include, adding a basic solution, such as ammonium hydroxide, to the mixture so that a pH value of the mixture is at least 11.

[0033] In various embodiments, the method may also include stirring the mixture after adding the basic solution to the mixture. The method may also include filtering the mixture to form the precursor solution before depositing the precursor solution on the seed layer. The mixture may be filtered using a glass fiber filter. The precursor solution including zinc nitrate and ammonium hydroxide may be collected as the filtrate, while the insoluble zinc oxide may be retained on the filter. The precursor solution may include zinc cations, ammonium cations, nitrates anions, and hydroxide anions.

[0034] The method may also include providing ultraviolet (UV) radiation after and/or during depositing the precursor solution on the seed layer, e.g. using an UV source such as an UV lamp.

[0035] In various embodiments, the method may be carried out in a non-vacuum environment. The method may be carried out at about atmospheric pressure.

[0036] In various embodiments, the substrate may be a glass substrate. The substrate may include glass.

[0037] In various other embodiments, the substrate may be a plastic or a polymer substrate. The substrate may include a plastic or a polymer, such as polyethylene terephthalate (PET).

[0038] In various embodiments, depositing the precursor solution and contacting the precursor solution with the aluminum metal may be carried out for a duration of any value within a range from 30 minutes to 120 minutes (inclusive of both end values). The aluminum-doped zinc oxide film may have a thickness of any value within a range from 60 nm to 80 nm (inclusive of both end values).

[0039] Various embodiments may relate to an aluminum-doped zinc oxide film formed by a method as described herein.

[0040] The aluminum-doped zinc oxide film may have a transmittance of more than 70%, e.g. more than 90%.

[0041] In various embodiments, the aluminum-doped zinc oxide film may have a sheet resistance of less than or equal to 200 ohms per square. The aluminum-doped zinc oxide film may have a sheet resistance of any value between 100 to 200 ohms per square (inclusive of both end values).

[0042] Various embodiments may be able to meet the requirements of applications such as touch screens, i.e. a sheet resistance of about 100-200 ohms /square, and/or a transmittance of around 90%.

[0043] In various embodiments, the aluminum-doped zinc oxide film may have an adhesion rating of class 5B.

[0044] In various embodiments, the aluminum-doped zinc oxide film may have or may form a smooth or planar surface.

[0045] In various embodiments, the aluminum-doped zinc oxide film may include a plurality of nanostructure, e.g. nanorods. The nanostructures may include AZO.

[0046] In various embodiments, the method may include forming a seed layer, e.g. a ZnO or AZO seed layer. The method may also include preparing a precursor solution. Ammonium citrate, ammonium nitrate and ZnO power may be mixed, and ammonium hydroxide may be added to form a mixture including insoluble ZnO, zinc nitrate and ammonium hydroxide. This mixture may be then filtered to remove the insoluble ZnO and may form the precursor solution including zinc nitrate and ammonium hydroxide. The precursor solution including zinc nitrate and ammonium hydroxide may then be deposited into the seed layer at a temperature of 85° or less under UV radiation to form the AZO film.

[0047] Various embodiments may relate to a composition or a precursor solution having a composition. The composition or precursor solution may include zinc nitrate and ammonium hydroxide.

[0048] FIG. 3 is a schematic illustrating a method of forming an aluminum-doped zinc oxide film according to various embodiments. As shown in FIG. 3, a substrate 302 may be provided, and

a seed layer 304 may be formed on the substrate 302. The seed layer 304 may be a ZnO seed layer, which may be prepared by spin- or dip coating the substrate 302 in a ZnO nanoparticle dispersion (10 mg mL^{-1}) in NH_4OH . The coated substrate 302 may be dried on a hotplate at temperatures $80 - 120^\circ\text{C}$ for 2 minutes resulting in $60 - 80 \text{ nm}$ thick seed layers 304.

[0049] A precursor solution may be deposited on the seed layer 304 to form the aluminum-doped zinc oxide film 306. Ammonium citrate, ammonium nitrate and zinc oxide powder may be mixed. Ammonium citrate may be dissolved in deionized water, while zinc oxide in ammonium nitrate may be suspended in deionized water. The ratio of ammonium citrate (1 mmol L^{-1}) : ammonium nitrate and ZnO powder (10 g L^{-1}) may be 5:5.

[0050] NH_4OH (28 weight percent or wt%) may be added until the pH of the mixture reaches a value > 11 . The mixture may be stirred overnight. The mixture may subsequently be filtered (using $0.45 \mu\text{m}$ glass fiber filters). The filtrate including zinc nitrite ($\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$) and ammonium hydroxide ($\text{NH}_3 \cdot \text{H}_2\text{O}$) may be stored in polyethylene (PE bottles) at room temperature until usage as the precursor solution. The dissolved zinc concentration in the precursor solution may be $36 \pm 4 \text{ mmol/L}$. Deposition of the precursor solution may be carried out at a temperature of 85°C for any time duration from 30 to 120 minutes (inclusive of both end values), depending on the desired film thickness. The film 306 may be grown under ultraviolet light irradiation. A piece of aluminum metal (not shown) may be dipped or immersed in the precursor solution before, during or after deposition on the seed layer.

[0051] Various embodiments may relate to a stacked arrangement including a substrate 302, a seed layer 304 on the substrate 302, and an aluminum-doped zinc oxide film 306 on the seed layer 304. Various embodiments may relate to an aluminum-doped zinc oxide film 306.

[0052] The most straightforward yet challenging approach for deposition of ZnO thin films may be aqueous solution growth. Various embodiments may relate to a method of processing highly transparent and conducting aluminum-doped ZnO (AZO) electrodes on substrates.

[0053] Various embodiments may relate to low-temperature and solution-phase deposition (by hydrothermal growth). These may together facilitate higher-throughput processing, which is desired by the industry. Various embodiments may allow potential use of temperature-intolerant plastic substrates for flexible optoelectronic applications.

[0054] Various embodiments may relate to a growth process that is relatively insensitive to the nature and quality of the seed layer applied to initiate growth.

[0055] Various embodiments may relate to a preparation process that is less time consuming and may waste less materials.

[0056] Various embodiments may result in an AZO film with surface morphology that is relatively smooth and featureless, that may allow subsequent active device layers to be deposited without issues such as short circuits or current leakage.

[0057] Various embodiments may relate to films with excellent optoelectronic properties. The films may be formed with a method having a process temperature not exceeding 85 °C, which is a substantial improvement compared to previously reported non-vacuum methods.

[0058] Various embodiments may relate to a film having a sheet resistance in the range of megaohms/square ($M\Omega/\text{square}$).

[0059] Various embodiments may relate to a precursor solution of zinc nitrate and ammonium hydroxide ($\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}:\text{NH}_3 \cdot \text{H}_2\text{O}$), in which the high quality growth of the AZO film may not be dependent on a high quality seed layer.

[0060] FIG. 4 is a plot of transmittance (in percent or %) as a function of wavelength (in nanometers or nm) showing the transmittance on films formed from a zinc oxide (ZnO) seed layer and an aluminum-doped zinc oxide (AZO) seed layer according to various embodiments. As shown in FIG. 4, the film formed using a ZnO seed layer may achieve a transmittance of more than 90% for a wavelength of about 800 nm and close to 90% for a wavelength of about 700 nm, and the film formed using AZO may achieve a transmittance close to 70% for a wavelength of about 800nm, and a transmittance of over 60% for a wavelength of about 700 nm. The films may achieve a transmittance of about 35 % to about 90% for wavelengths between 400 nm to 700 nm, which relate to wavelengths of visible light.

[0061] FIG. 5A is a scanning electron microscopy (SEM) image showing a top planar view of an aluminum-doped zinc oxide film grown using a zinc oxide (ZnO) seed layer according to various embodiments. FIG. 5B is another scanning electron microscopy (SEM) image showing a cross sectional side view of the aluminum-doped zinc oxide film shown in FIG. 5A according to various embodiments.

[0062] FIG. 5C is a scanning electron microscopy (SEM) image showing a top planar view of an aluminum-doped zinc oxide film grown using an aluminum-doped zinc oxide (AZO) seed layer according to various embodiments. FIG. 5D is another scanning electron microscopy (SEM) image showing a cross sectional side view of the aluminum-doped zinc oxide film shown in FIG. 5C according to various embodiments.

[0063] FIG. 6A is a scanning electron microscopy (SEM) image showing a top planar view of an aluminum-doped zinc oxide film grown using an aluminum-doped zinc oxide (AZO) seed layer and an original bath recipe according to various embodiments. FIG. 6B is a scanning electron microscopy (SEM) image showing a top planar view of an aluminum-doped zinc oxide film grown using a zinc oxide (ZnO) seed layer and an original bath recipe according to various embodiments.

[0064] FIG. 6C is a scanning electron microscopy (SEM) image showing a top planar view of an aluminum-doped zinc oxide film grown using an aluminum-doped zinc oxide (AZO) seed layer and a 50 : 50 bath recipe according to various embodiments. FIG. 6D is a scanning electron microscopy (SEM) image showing a top planar view of an aluminum-doped zinc oxide film grown using a zinc oxide (ZnO) seed layer and a 50 : 50 bath recipe according to various embodiments. The original bath recipe may include ZnO and $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ in ratio 50 : 50 by weight percent (wt %). The 50 : 50 bath recipe may include 50 weight percent of ZnO and $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ and 50% of deionized water.

[0065] FIG. 7 is a table comparing the sheet resistances (in ohms per square or $\Omega/\square$) of a aluminum-doped zinc oxide film grown using an aluminum-doped zinc oxide (AZO) seed layer and an aluminum-doped zinc oxide film grown using a zinc oxide (ZnO) seed layer according to various embodiments. Three samples are tested for each seed layer and the average sheet resistance may be computed based on the three samples.

[0066] FIG. 8 is a plot of transmittance T (in percent or %) as a function of wavelengths (in nanometers or nm) showing the transmittance of aluminum-doped zinc oxide films according to various embodiments as well as the transmittance of conventional glasses. 1 mm glass refers to a common glass sample, b-glass refers to substrate glass, Z1-Z3 refer to different samples of AZO films formed with different thicknesses of ZnO seed layers on b-glass (silicate glass), and A1- A8 refer to different samples of AZO films formed with different thicknesses of AZO seed layers on b-glass.

[0067] FIG. 9 is a table comparing the sheet resistance (in ohms/square (sq)) and transmittance (in percent or %) of various aluminum-doped zinc oxide films grown over various substrates. A first transmittance reading may be based on a combination of the aluminum-doped zinc oxide film with the substrate and the seed layer, while a second transmittance reading may be based on the aluminum-doped zinc oxide film alone (without the substrate and the seed layer). The substrates are silicate glass (SG1) and polyethylene terephthalate (PET).

[0068] FIG. 10 shows an optical image of a glass having a first portion coated with a film according to various embodiments and a second portion uncoated.

[0069] FIG. 11 shows images of a potential application of a film according to various embodiments.

[0070] Various embodiments may relate to a formula for a growth solution of an aluminum-doped zinc oxide film. The film formed using the formula may be insensitive to the nature and quality of the seed layer. Various embodiments may lead to a substantial reduction the material and process costs. Various embodiments may be less time consuming and may waste less material. The formulation may be suitable for the aqueous solution deposition of aluminum-doped (Al-doped) ZnO. The new formula may be suitable for AZO, ZnO or any other suitable seed layer. Various embodiments may involve use of chemical materials that are commercially available and cheap. Various embodiments may involve growth using formula solution. Various embodiments may not require vacuum and may not require high energy, thus saving energy.

[0071] Various embodiments may relate to a film having excellent properties which are achieved at process temperatures not exceeding 85°, which may be a substantial improvement compared to films formed by previously reported non-vacuum methods.

[0072] Various embodiments may involve or relate to low-temperature and solution-phase deposition (by hydrothermal growth). These features may together facilitate higher-throughput processing which is desired by the industry. Various embodiments may allow potential use of temperature-intolerant plastic substrates for flexible optoelectronic applications. Various embodiments may result or relate to a film that may be coated on a large area substrate.

[0073] Various embodiments may involve or relate to a growth formula that is relatively insensitive to the nature and quality of the seed layer applied to initiate growth, thus reducing the material costs greatly.

[0074] Various embodiments may involve or relate to a preparation process that is less time consuming and materials wasting.

[0075] Various embodiments may relate to or result a film with a surface morphology that is relatively smooth and featureless.

[0076] Various embodiments may relate to or result a film with an adhesion of level 5B.

[0077] While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

CLAIMS

1. A method of forming an aluminum-doped zinc oxide film, the method comprising:
forming a seed layer on a substrate by a solution deposition process;
depositing a precursor solution comprising zinc nitrate and ammonium hydroxide on the seed layer; and
contacting the precursor solution with aluminum metal at a temperature equal to or less than 85 °C;
wherein the aluminum-doped zinc oxide film is formed from the precursor solution and the aluminum metal.
2. The method according to claim 1,
wherein the seed layer comprises zinc oxide.
3. The method according to claim 2,
wherein forming the seed layer comprises:
depositing a dispersion comprising zinc oxide nanoparticles on the substrate; and
heating the deposited zinc oxide nanoparticles to form the seed layer.
4. The method according to claim 3,
wherein depositing the dispersion on the substrate comprises spin coating or dip coating the substrate with the dispersion.
5. The method according to claim 1,
wherein the seed layer comprises aluminum-doped zinc oxide.
6. The method according to any one of claims 1 to 5, further comprising:

forming a mixture comprising zinc oxide, zinc nitrate and ammonium hydroxide by mixing ammonium citrate, ammonium nitrate and zinc oxide powder.

7. The method according to claim 6, further comprising:
adding a basic solution to the mixture so that a pH value of the mixture is at least 11.
8. The method according to claim 7,
wherein the basic solution is ammonium hydroxide.
9. The method according to claim 7 or claim 8, further comprising:
stirring the mixture after adding the basic solution to the mixture; and
filtering the mixture to form the precursor solution before depositing the precursor solution on the seed layer.
10. The method according to any one of claims 1 to 9,
wherein the method is carried out in a non-vacuum environment.
11. The method according to any one of claims 1 to 10,
wherein the substrate comprises glass.
12. The method according to any one of claims 1 to 10,
wherein the substrate comprises polyethylene terephthalate (PET).
13. The method according to any one of claims 1 to 12,
wherein depositing the precursor solution and contacting the precursor solution with the aluminum metal is carried out for a duration of any value within a range from 30 minutes to 120 minutes.
14. The method according to any one of claims 1 to 13,

wherein the aluminum-doped zinc oxide film has a thickness of any value within a range from 60 nm to 80 nm.

15. An aluminum-doped zinc oxide film formed by a method according to any one of claims 1 to 14.
16. The aluminum-doped zinc oxide film according to claim 15,
wherein the aluminum-doped zinc oxide film has a transmittance of more than 70%.
17. The aluminum-doped zinc oxide film according to claim 15,
wherein the aluminum-doped zinc oxide film has a transmittance of more than 90%.
18. The aluminum-doped zinc oxide film according to any one of claims 15 to 17,
wherein the aluminum-doped zinc oxide film has sheet resistance of less than 200 ohms per square.
19. The aluminum-doped zinc oxide film according to any one of claims 15 to 18,
wherein the aluminum-doped zinc oxide film has an adhesion rating of class 5B.
20. The aluminum-doped zinc oxide film according to any one of claims 15 to 19,
wherein the aluminum-doped zinc oxide film has a smooth surface.