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(54) Title: PROCESS FOR PREPARING NANO-POROUS METAL OXIDE SEMICONDUCTOR LAYERS

(57) Abstract: A process for preparing a layer of a nano-porous metal oxide semiconductor comprising the steps of: (i) providing metal oxide semiconductor nano-particles prepared by a wet precipitation process, (ii) heating said nano-particles at a temperature in the range of 250 to 600 °C, (iii) preparing a dispersion of said heat-treated nano-particles from step (ii), (iv) applying said dispersion prepared in step (iii) to a support to produce a coating; and (v) subjecting said coating to a pressure in the range of 100 to 1000 bar at a temperature below 250 °C; a layer of a nano-porous metal oxide semiconductor obtainable by this process; and a photovoltaic device comprising a layer of a nano-porous metal oxide semiconductor obtainable by this process.

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PROCESS FOR PREPARING NANO-POROUS METAL OXIDE SEMICONDUCTOR LAYERS

Field of the invention

5 The present invention relates to a process for preparing nano-porous metal oxide semiconductor layers.

Background of the invention.

10 There are two basic types of photoelectrochemical photovoltaic cells. The first type is the regenerative cell which converts light to electrical power leaving no net chemical change behind. Photons of energy exceeding that of the band gap generate electron-hole pairs, which are separated by the electrical field present in
15 the space-charge layer. The negative charge carriers move through the bulk of the semiconductor to the current collector and the external circuit. The positive holes are driven to the surface where they are scavenged by the reduced form of the redox relay molecular (R), oxidizing it: $h^+ + R \rightarrow O$, the oxidized form. O is
20 reduced back to R by the electrons that re-enter the cell from the external circuit. In the second type, photosynthetic cells, operate on a similar principle except that there are two redox systems: one reacting with the holes at the surface of the semiconductor electrode and the second reacting with the electrons
25 entering the counter-electrode. In such cells water is typically oxidized to oxygen at the semiconductor photoanode and reduced to hydrogen at the cathode. Titanium dioxide has been the favoured semiconductor for these studies.

Mesoscopic or nano-porous semiconductor materials, minutely
30 structured materials with an enormous internal surface area, have been developed for the first type of cell to improve the light capturing efficiency by increasing the area upon which the spectrally sensitizing species could adsorb. Arrays of nano-crystals of oxides such as TiO_2 , ZnO , SnO_2 and Nb_2O_5 , or chalcogenides
35 such as $CdSe$ are the preferred semiconductor materials and are interconnected to allow electrical conduction to take place. A wet type solar cell having a porous film of dye-sensitized titanium dioxide semiconductor particles as a work electrode was expected to surpass an amorphous silicon solar cell in conversion efficiency
40 and cost. These fundamental techniques were disclosed in 1991 by Graetzel et al. in Nature, volume 353, pages 737-740 and in US 4,927,721, US 5,350,644 and JP-A 05-504023. Graetzel et al

reported solid-state dye-sensitized mesoporous TiO₂ solar cells with up to 33% photon to electron conversion efficiencies.

In 1995 Tennakone et al. in Semiconductor Sci. Technol., volume 10, page 1689 and O'Regan et al. in Chem. Mater., volume 7, 5 page 1349 reported an all-solid-state solar cell consisting of a highly structured hetero-junction between a p- and n-type semiconductor with a absorber in between in which the p-semiconductor is CuSCN or CuI, the n-semiconductor is nano-porous titanium dioxide and the absorber is an organic dye.

10 EP-A 1 176 646 discloses a solid state p-n heterojunction comprising an electron conductor and a hole conductor, characterized in that it further comprises a sensitizing semiconductor, said sensitizing being located at an interface between said electron conductor and said hole conductor; and its 15 application in a solid state sensitized photovoltaic cell.

A drawback in the manufacture of nano-porous metal oxide semiconductor layers for Graetzel photovoltaic cells is the high temperature needed for making the nano-porous metal oxide semiconductor layer. This is apparently needed to obtain sufficient 20 contact between the nano-porous metal oxide particles to create a conductive pathway for the photogenerated charges (electrons). Although the term sintering is not the appropriate one in this context, this term is often used to describe this heating process. Usually temperatures between 300 and 550°C are applied for 15 to 90 25 minutes. Such high temperatures are prohibitive for making photovoltaic cells on plastic and flexible substrates. Such cells would offer a myriad of advantages for this type of photovoltaic cell.

WO 00/72373 discloses a method for manufacturing a 30 nanostructured porous film electrode, the method characterized by the steps of: preparing a binder-free suspension (21) of electrode material particles (11) in a volatile suspending agent (13), said particles substantially having a size within the nanometer scale, depositing the binder-free particle suspension (21) on a substrate 35 (22) covered with a conducting film, removing the suspending agent (31) by evaporation, and compressing the particles to form an electrically conducting and mechanically stable nanostructured porous film. The process of WO 00/72373 enables the realization of the same solar cell performance with high pressure sintered nano- 40 porous titanium dioxide layers as with conventional high temperature sintering. This finding was confirmed in 2000 by Pichot et al. in Langmuir, volume 16, pages 5625 to 5630, and in

2001 by Lindstrom et al. in Nano Letters, volume 1, pages 97 to 100. However, although this high pressure sintering process appears to work quite well with Degussa P25, a nano-sized titanium dioxide with a mean particle size of 30 nm and a specific surface
5 of 50 m²/g from DEGUSSA, on a glass substrate or a plastic substrate, it has been found not to work with titanium dioxide particles made by a wet precipitation process.

There is therefore a need for a low temperature process for preparing nano-porous metal oxide semiconductor layers with nano-
10 particles prepared by wet precipitation processes on supports.

Aspects of the invention.

It is therefore an aspect of the present invention to provide
15 a process for preparing nano-porous metal oxide semiconductor layers with nano-particles prepared by a wet precipitation process on both flexible and rigid supports.

It is a further aspect of the present invention to provide a photovoltaic cell incorporating a nano-porous metal oxide
20 semiconductor layer prepared with nano-particles prepared by a wet precipitation process on flexible and rigid supports.

Further aspects and advantages of the invention will become apparent from the description hereinafter.

25 Summary of the invention.

It has been surprisingly found that layers of nano-porous metal oxide semiconductors can be prepared with nano-particles prepared by a wet precipitation process on supports by a process
30 involving preheating the nano-particles at a temperature of 250 to 600°C, applying a coating of these preheated nano-particles to the support and subjecting the coating to a pressure of 100 to 1000 bar, without the application of the high temperatures needed for conventional sintering of titanium dioxide nano-particles i.e. 300
35 to 550°C.

Aspects of the present invention are realized by a process for preparing a layer of a nano-porous metal oxide semiconductor comprising the steps of: (i) providing metal oxide semiconductor nano-particles prepared by a wet precipitation process, (ii)
40 heating said nano-particles at a temperature in the range of 250 to 600°C, (iii) preparing a dispersion of the heat-treated nano-particles from step (ii), (iv) applying the dispersion of step

(iii) to a support to produce a coating; and (v) subjecting said coating to a pressure in the range of 100 to 1000 bar at a temperature below 250°C. An electrically conducting and mechanically stable nano-porous metal oxide semiconductor layer is
5 thereby prepared.

Aspects of the present invention are also realized by a layer of a nano-porous metal oxide semiconductor obtainable by the above-mentioned process.

Aspects of the present invention are also realized by a
10 photovoltaic device comprising a layer of a nano-porous metal oxide semiconductor obtainable by the above-mentioned process.

Preferred embodiments are disclosed in the dependent claims.

Detailed description of the invention.

15

Definitions

The term nano-porous metal oxide semiconductor means a metal oxide semiconductor having pores with a size of 100 nm or less and
20 having an internal surface area of at least 5 m²/g and not more than 300 m²/g.

The term chalcogenide means a binary compound containing a chalcogen and a more electropositive element or radical. A chalcogen is an element from group IV of the periodic table
25 including oxygen, sulphur, selenium, tellurium and polonium.

The term "support" means a "self-supporting material" so as to distinguish it from a "layer" which may be coated on a support, but which is itself not self-supporting. It also includes any treatment necessary for, or layer applied to aid, adhesion to the support.

30 The term continuous layer refers to a layer in a single plane covering the whole area of the support and not necessarily in direct contact with the support.

The term non-continuous layer refers to a layer in a single plane not covering the whole area of the support and not
35 necessarily in direct contact with the support.

The term coating is used as a generic term including all means of applying a layer including all techniques for producing continuous layers, such as curtain coating, doctor-blade coating etc., and all techniques for producing non-continuous layers such
40 as screen printing, ink jet printing, flexographic printing, and techniques for producing continuous layers.

The abbreviation PEDOT represents poly(3,4-ethylenedioxy-thiophene).

The abbreviation PSS represents poly(styrene sulphonic acid) or poly(styrenesulphonate).

5

Process for preparing a layer of a nano-porous metal oxide semiconductor

Aspects of the present invention are realized by a process for
10 preparing a layer of a nano-porous metal oxide semiconductor
comprising the steps of: (i) providing metal oxide semiconductor
nano-particles prepared by a wet precipitation process, (ii)
heating said nano-particles at a temperature in the range of 250 to
600°C, (iii) preparing a dispersion of the heat-treated nano-
15 particles from step (ii), (iv) applying the dispersion of step
(iii) to a support to produce a coating; and (v) subjecting said
coating to a pressure in the range of 100 to 1000 bar at a
temperature below 250°C.

According to a first embodiment of the process, according to
20 the present invention, the metal oxide semiconductor is n-type.

According to a second embodiment of the process, according to
the present invention, the nano-porous metal oxide semiconductor
has a band-gap of greater than 2.9 eV.

According to a third embodiment of the process, according to
25 the present invention, the nano-porous metal oxide semiconductor
nano-particle have a mean number averaged particle size ≤ 20 nm.

According to a fourth embodiment of the process, according to
the present invention, the nano-porous metal oxide semiconductor is
selected from the group consisting of titanium oxides, tin oxides,
30 niobium oxides, tantalum oxides, tungsten oxides and zinc oxides.

According to a fifth embodiment of the process, according to
the present invention, the nano-porous metal oxide semiconductor is
titanium dioxide.

According to a sixth embodiment of the process, according to
35 the present invention, the nano-porous metal oxide semiconductor is
titanium dioxide and between 80 and 100% thereof has an anatase
morphology.

According to a seventh embodiment of the process, according to
the present invention, the nano-porous metal oxide semiconductor is
40 titanium dioxide and between 90 and 100% thereof has an anatase
morphology.

According to an eighth embodiment of the process, according to the present invention, the pretreatment temperature is in the range of 300 to 500°C.

According to a ninth embodiment of the process, according to
5 the present invention, the pretreatment temperature is in the range of 350 to 450°C.

According to a tenth embodiment of the process, according to the present invention, the sintering pressure is in the range of 300 to 700 bar. According to an eleventh embodiment of the
10 process, according to the present invention, the sintering pressure is in the range of 400 to 600 bar.

According to a twelfth embodiment of the process, according to the present invention, the process further comprises heating the coating subjected to pressure from step (v) at a temperature of 100
15 to 200°C. According to a thirteenth embodiment of the process, according to the present invention, the process further comprises heating the coating subjected to pressure from step (v) at a temperature of 125 to 170°C.

According to a fourteenth embodiment of the process, according
20 to the present invention, step (v) is carried out at a temperature above 0°C.

Step (ii) of the process, according to the present invention, is carried out under the atmosphere and pressure necessary to obtain metal oxide nano-particles with semiconducting properties.
25 According to a fifteenth embodiment of the process, according to the present invention, step (ii) is carried out at under an ambient atmosphere i.e. at the pertaining ambient pressure and under the pertaining ambient atmosphere.

The sintering pressure for a particular layer of a nano-porous
30 metal oxide semiconductor is dependent upon the nature of the support, a sintering pressure of 300 to 700 bar being suitable for glass supports and sintering pressures up to 1000 bar being suitable for polymeric film supports.

For efficient solar cells, the coating of the nano-porous TiO₂
35 should be between 8 and 12 µm in order to have sufficient light absorption for generating power conversion efficiencies up to 5 to 8%. The thicker the titanium dioxide coating, the longer the pathway for the charges (electrons) have to be transported to the charge collecting electrode and the greater the probability of
40 recombination occurring with resultant power conversion efficiency loss. In order to circumvent this problem smaller titanium dioxide nano-particles can be used, having a larger specific surface and

hence enabling thinner layers to be realized with the same light absorbance values. In this way, photovoltaic cells with higher efficiencies can be obtained due to the fact that the probability of recombination is reduced due to the path traversed by the
 5 electrons to the charge collecting electrode being shorter.

Step (i) of the process, according to the present invention, provides metal oxide semiconductor nano-particles prepared by a wet precipitation process. The expression "wet precipitation process" distinguishes the metal oxide semiconductor nano-particles used in
 10 the process, according to the present invention, from those prepared by non-wet chemical processes such as flame pyrolysis processes such as that operated by Degussa. Suitable titanium dioxide nano-particles produced by wet precipitation processes include:

15

Ti-Nanoxide™ T	=	a nano-sized anatase titanium dioxide with a mean particle size of 13 nm and a specific surface of 120 m ² /g from SOLARONIX SA;
Ti-Nanoxide™ HT	=	a nano-sized anatase titanium dioxide with a mean particle size 9 nm and specific surface of 165 m ² /g from SOLARONIX SA;

which are often used as n-type semi-conductor nano-particles in making Graetzel-type photovoltaic cells, but can be also readily synthesized using fairly straightforward precipitation techniques
 20 familiar in colloid chemistry, such as described, for example, in 1997 by Barbe et al in Journal of the American Ceramic Society, volume 80(12), pages 3157 - 3171, herein incorporated by reference.

Spectral sensitization of nano-porous metal oxide semiconductor
 25 layers

Aspects of the present invention are also realized by a layer of a nano-porous metal oxide semiconductor obtainable by a process, according to the present invention.

30 According to a first embodiment of the layer, according to the present invention, the layer contains at least one spectral sensitizer for the nano-porous metal oxide semiconductor selected from the group consisting of metal chalcogenide nano-particles with a band-gap between 1.5 and 2.9 eV, organic dyes, and metallo-
 35 organic dyes.

According to a second embodiment of the layer, according to the present invention, the layer contains at least one spectral sensitizer for the nano-porous metal oxide semiconductor selected from the group consisting of metal oxides, metal sulphides and
5 metal selenides.

According to a third embodiment of the layer, according to the present invention, the layer contains at least one spectral sensitizer for the nano-porous metal oxide semiconductor which is a metal sulphide.

10 According to a fourth embodiment of the layer, according to the present invention, the layer contains at least one spectral sensitizer for the nano-porous metal oxide semiconductor selected from the group consisting of lead sulphide, bismuth sulphide, cadmium sulphide, silver sulphide, antimony sulphide, indium
15 sulphide, copper sulphide, cadmium selenide, copper selenide, indium selenide, cadmium telluride or a mixture of two or more thereof.

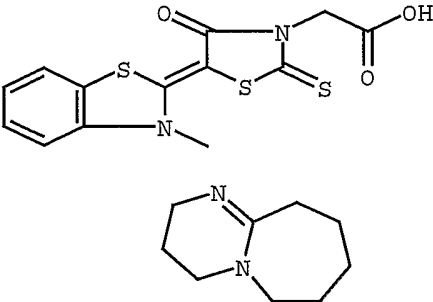
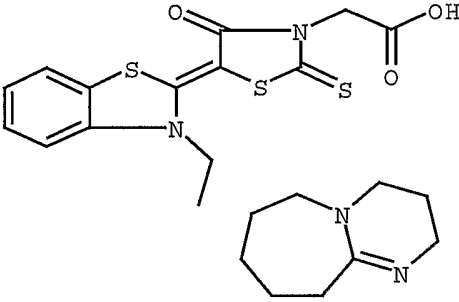
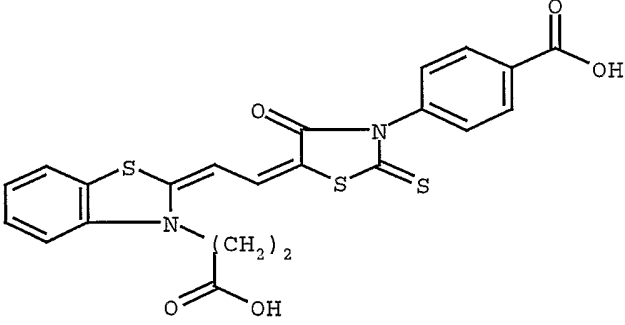
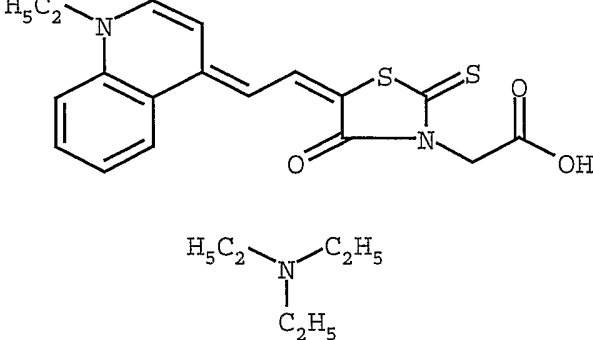
Vogel et al. in 1990 in Chemical Physics Letters, volume 174, page 241, herein incorporated by reference, reported the
20 sensitization of highly porous TiO_2 with in-situ prepared quantum size CdS particles (40-200Å), a photovoltage of 400 mV being achieved with visible light and high photon to current efficiencies of greater than 70% being achieved at 400 nm and an energy conversion efficiency of 6.0% under monochromatic illumination with
25 $\lambda = 460$ nm. In 1994 Hoyer et al. reported in Applied Physics, volume 66, page 349, that the inner surface of a porous titanium dioxide film could be homogeneously covered with isolated quantum dots and Vogel et al. reported in Journal of Physical Chemistry, volume 98, pages 3183-3188, herein incorporated by reference, the
30 sensitization of various nanoporous wide-bandgap semiconductors, specifically TiO_2 , Nb_2O_5 , Ta_2O_5 , SnO_2 and ZnO , with quantum-sized PbS, CdS, Ag_2S , Sb_2S_3 and Bi_2S_3 and the use of quantum dot-sensitized oxide semiconductors in liquid junction cells. The internal photocurrent quantum yield decreased with increasing particle
35 diameter and decreased in the order $\text{TiO}_2 > \text{ZnO} > \text{Nb}_2\text{O}_5 > \text{SnO}_2 > \text{Ta}_2\text{O}_5$.

EP-A 1 176 646, herein incorporated by reference, discloses a solid state p-n heterojunction comprising an electron conductor and a hole conductor, characterized in that it further comprises a
40 sensitizing semiconductor, said sensitizing being located at an interface between said electron conductor and said hole conductor; and its application in a solid state sensitized photovoltaic cell.

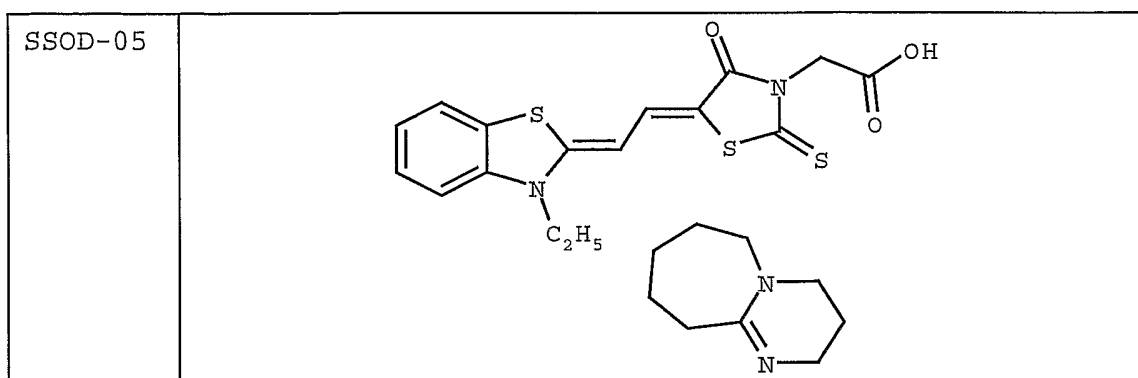
In a preferred embodiment the sensitizing semiconductor is in the form of particles adsorbed at the surface of said electron conductor and in a further preferred embodiment the sensitizing semiconductor is in the form of quantum dots, which according to a particularly preferred embodiment are particles consisting of PbS, CdS, Bi₂S₃, Sb₂S₃, Ag₂S, InAs, CdTe, CdSe or HgTe or solid solutions of HgTe/CdTe or HgSe/CdSe.

Suitable spectrally sensitizing organic dyes (SSOD) include cyanine, merocyanine and anionic dyes, such as:

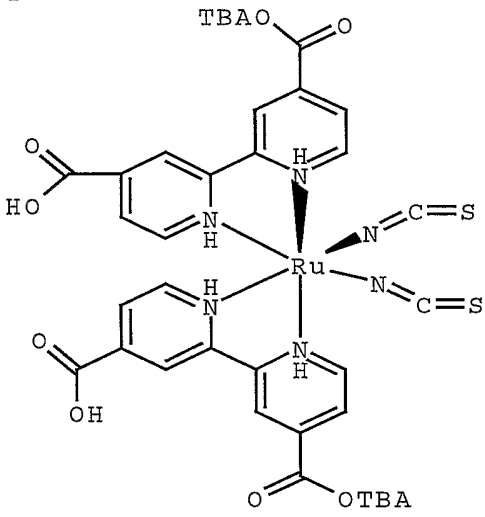
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SSOD-01	
SSOD-02	
SSOD-03	
SSOD-04	

10



Suitable spectrally sensitizing metallo-organic dyes allowing for broad absorption of the solar spectrum include:

	chemical name
Ruthenium 470, a ruthenium dye from Solaronix	tris(2,2'-bipyridyl-4,4' dicarboxylato) ruthenium (II) dichloride
Ruthenium 505, a ruthenium dye from Solaronix	cis-bis(isocyanato) (2,2'-bipyridyl-4,4' dicarboxylato) ruthenium (II)
Ruthenium 535, a ruthenium dye from Solaronix	cis-bis(isothiocyanato)bis(2,2'-bipyridyl-4,4'-dicarboxylato)-ruthenium(II)
Ruthenium 535 bis-TBA, a ruthenium dye from Solaronix	cis-bis(isothiocyanato)bis(2,2'-bipyridyl-4,4'-dicarboxylato)-ruthenium(II) bis-tetrabutylammonium
	
Ruthenium 620 "Black Dye", a ruthenium dye from Solaronix	(anion only) tris(isothiocyanato)-ruthenium(II)-2,2':6',2"-terpyridine-4,4',4"-tricarboxylic acid

5

Support

Supports for use according to the present invention include polymeric films, silicon, ceramics, oxides, glass, polymeric film

reinforced glass, glass/plastic laminates, metal/plastic laminates, paper and laminated paper, optionally treated, provided with a subbing layer or other adhesion promoting means to aid adhesion to the layer configuration, according to the present invention.

5 Suitable polymeric films are poly(ethylene terephthalate), poly(ethylene naphthalate), polystyrene, polyethersulphone, polycarbonate, polyacrylate, polyamide, polyimides, cellulose triacetate, polyolefins and poly(vinyl chloride), optionally treated by corona discharge or glow discharge or
10 provided with a subbing layer.

Photovoltaic devices

Aspects of the present invention are realized by a
15 photovoltaic device comprising a layer of a nano-porous metal oxide semiconductor obtainable by a process, according to the present invention.

Photovoltaic devices comprising a layer of a nano-porous metal oxide semiconductor prepared by a process, according to the present
20 invention, can be of two types: the regenerative type which converts light into electrical power leaving no net chemical change behind in which current-carrying electrons are transported to the anode and the external circuit and the holes are transported to the cathode where they are oxidized by the electrons from the external
25 circuit and the photosynthetic type in which there are two redox systems one reacting with the holes at the surface of the semiconductor electrode and one reacting with the electrons entering the counter-electrode, for example, water is oxidized to oxygen at the semiconductor photoanode and reduced to hydrogen at
30 the cathode. In the case of the regenerative type of photovoltaic cell, as exemplified by the Graetzel cell, the hole transporting medium may be a liquid electrolyte supporting a redox reaction, a gel electrolyte supporting a redox reaction, an organic hole transporting material, which may be a low molecular weight material
35 such as 2,2',7,7'-tetrakis(N,N-di-p-methoxyphenyl-amine)9,9'-spirobifluorene (OMeTAD) or triphenylamine compounds or a polymer such as PPV-derivatives, poly(N-vinylcarbazole) etc., or inorganic semiconductors such as CuI, CuSCN etc. The charge transporting process can be ionic, as for example in the case of a liquid
40 electrolyte or gel electrolyte or electronic, as for example in the case of organic or inorganic hole transporting materials.

Such regenerative photovoltaic devices can have a variety of internal structures in conformity with the end use. Conceivable forms are roughly divided into two types: structures which receive light from both sides and those which receive light from one side.

5 An example of the former is a structure made up of a transparently conductive layer e.g. an ITO-layer or a PEDOT/PSS-containing layer and a transparent counter electrode electrically conductive layer e.g. an ITO-layer or a PEDOT/PSS-containing layer having interposed therebetween a photosensitive layer and a charge transporting

10 layer. Such devices preferably have their sides sealed with a polymer, an adhesive etc. to prevent deterioration or volatilization of the inside substances. The external circuit connected to the electrically-conductive substrate and the counter electrode via the respective leads is well-known.

15 Alternatively the layer of a nano-porous metal oxide semiconductor prepared by a process, according to the present invention, can be incorporated in hybrid photovoltaic compositions such as described in 1991 by Graetzel et al. in Nature, volume 353, pages 737-740, in 1998 by U. Bach et al. [see Nature, volume 395,

20 pages 583-585 (1998)] and in 2002 by W. U. Huynh et al. [see Science, volume 295, pages 2425-2427 (2002)].

Industrial application

25 Layers of nano-porous metal oxide semiconductors prepared according the process, according to the present invention, can be used in both regenerative and photosynthetic photovoltaic devices.

The invention is illustrated hereinafter by way of reference

30 and invention photovoltaic devices. The percentages and ratios given in these examples are by weight unless otherwise indicated.

EXAMPLE 1

35 Preparation of Titanium dioxide nano dispersions

Dispersion 1:

P25 a nano-sized titanium dioxide with a mean particle size of

40 25 nm and a specific surface of 55 m²/g from DEGUSSA was mixed with ethanol to give a 25% by weight of solid material and then treated ultrasonically to produce Dispersion 1.

Dispersion 2:

285 g of Ti-isopropoxide, 1800 mL of deionized water and 12.5
5 mL of nitric acid were stirred overnight at 80°C without a cover.
The total volume was made up to 1400 mL with deionized water and
then autoclaved at 230°C for 14 hours. The concentration of the
autoclaved colloid was reduced by evaporation to 16.2% by weight
of solid material and then sufficient ethanol added to give a final
10 solids content of 10.8% by weight, thereby producing Dispersion 2
(mean particle size of 13 nm, specific surface area 120 m²/g).

Dispersion 3:

15 Ti-Nanoxide™ T from SOLARONIX, having a mean particle size of
13 nm, a specific surface of 120 m²/g and containing 11% by weight
of titanium oxide is called dispersion 3.

Heat pretreatment of the Titanium dioxide nano dispersions

20

Dispersions 2 or 3 were dried in a rotary evaporator, ground,
spread on a sheet of glass and heated at 200, 350, 400 or 450°C,
depending on the experiment, for 30 minutes in a rotary tube
furnace. The resulting powders were then cooled, ground again and
25 converted into a paste by adding water, ethanol and 10-20 µL of
nitric acid. To prevent material loss, the paste was diluted with
water and put in a bottle. The excess liquid was evaporated at a
temperature of 100-150°C prior to use.

30 Evaluation in photovoltaic devices with liquid electrolyte

Photovoltaic devices 1-46 were prepared by the following procedure:

Preparation of the front electrode:

35

A glass plate (2 x 7 cm²) coated with conductive SnO₂:F
(Pilkington TEC15/3) with a surface conductivity of ca 15
Ohm/square was ultrasonically cleaned in isopropanol for 5 minutes
and then dried. The electrode was taped off at the borders and was
40 doctor blade-coated in the middle (0.7 x 4.5 cm²) with the titanium
dioxide colloidal dispersion with or without dilution with ethanol
depending upon the desired layer thickness.

The layer thickness was determined mechanically with a diamond-tipped probe (Perthometer) and interferometry and are given in Tables 1 to 4.

- 5 i) *Front electrodes prepared by high temperature sintering of nano-porous titanium dioxide layers:*

Coated glass electrodes with the nano titanium dioxide dispersions were heated at 450°C for 30 minutes, then cooled to
10 150°C by placing it on a hot plate at 150°C for 10 minutes, then immediately immersed in a 2×10^{-4} M solution of the Ruthenium 535 dye (SOLARONIX) for 15 to 17 hours followed by rinsing with acetonitrile to remove the non-adsorbed dye and drying at 50°C for several minutes. The front electrode thereby produced was
15 immediately used in assembling the corresponding photovoltaic cell.

- ii) *Front electrodes prepared by high pressure sintering of nano-porous titanium dioxide layers:*

20 Coated glass electrodes with the nano titanium dioxide dispersions were first dried at 110°C for 5 minutes, then, after cooling to room temperature (25°C), a pressure of 500 bars was applied for 5 seconds. These pressure sintered coatings were then heated to 110-150°C, then immediately immersed in a 2×10^{-4} M
25 solution of the Ruthenium 535 bis-TBA dye (SOLARONIX) for 15 to 17 hours followed by rinsing with acetonitrile to remove non-adsorbed dye and drying at 50°C for several minutes. The front electrode thereby produced was immediately used in assembling the corresponding photovoltaic cell.

30

Cell assembly

The back electrode (consisting of $\text{SnO}_2\text{:F}$ glass (Pilkington TEC15/3) evaporated with platinum to catalyze reduction of the electrolyte)
35 was sealed together with the front electrode with two pre-patterned layers of Surlyn® (DuPont) ($2 \times 7 \text{ cm}^2$ where in the middle $1 \times 6 \text{ cm}^2$ had been removed) in between. This was performed at a temperature just above 100°C on a hotplate. As soon as the sealing was completed, the cell was cooled to room temperature (25°C) and
40 electrolyte was added through holes in the counter electrode. The electrolyte used was a solution of 0.5 M LiI, 0.05 M I_2 and 0.4 M t-butylpyridine in acetonitrile and was injected into the cell

during cell assembly. The holes were then sealed with Surlyn® and a thin piece of glass. Conductive tape was attached on both long sides of the cell to collect the electricity during measurement. Measurements were performed immediately after cell assembly.

5

Device characterisation:

The cell was irradiated with a Steuernagel Solar Constant 575 solar simulator with a metal halide 1 AM light source. The
10 simulator was adjusted to about 1 sun equivalent. The electricity generated was recorded with a Type 2400 SMU Keithley electrometer.

The most relevant parameter for these experiments was the short circuit current (I_{sc}) which is given for the examples in Tables 1 to 4. The open circuit voltage was in all cases almost
15 the same (0.640 to 0.680), which was also the case for the fill factor (FF) (0.5 to 0.6). Cells with lower open circuit voltages than 0.640 V or fill factors lower than 0.5 were not considered.

i) *Photovoltaic devices incorporating sintered titanium dioxide*
20 *layers prepared with Dispersion 1:*

The device parameters for reference photovoltaic devices incorporating front electrodes with sintered titanium dioxide prepared with Dispersion 1 together with the sintering conditions
25 are given in Table 1.

Table 1:

Device	TiO ₂ dispersion	Heat pre-treatment	Pretreatment temperature [°C]	Sintering conditions	Layer thickness (µm)	I_{sc} [mA/cm ²]
1(ref)	1	No	-	450°C	3.2	4.76
2(ref)	1	No	-	450°C	3.6	4.56
3(ref)	1	No	-	450°C	4.8	5.49
4(ref)	1	No	-	450°C	8.0	5.40
5(ref)	1	No	-	450°C	17.0	5.80
6(ref)	1	No	-	Pressure	1.4	1.32
7(ref)	1	No	-	Pressure	2.1	1.68
8(ref)	1	No	-	Pressure	2.5	2.58
9(ref)	1	No	-	Pressure	4.0	4.90
10(ref)	1	No	-	Pressure	5.5	4.37
11(ref)	1	No	-	Pressure	5.9	5.19
12(ref)	1	No	-	Pressure	9.5	4.58
13(ref)	1	No	-	Pressure	16.0	5.50

The results in Table 1 show that Devices incorporating high pressure sintered titanium dioxide layers prepared with Dispersion 1 yielded, for similar layer thicknesses, comparable short circuit currents, I_{sc} , to Devices incorporating high temperature sintered titanium dioxide layers, as to be expected from the teaching of WO 00/72373.

ii) *Photovoltaic devices incorporating sintered titanium dioxide layers prepared with Dispersions 1 and 2:*

The short circuit currents, I_{sc} , for photovoltaic devices incorporating front electrodes with sintered titanium dioxide layers prepared with Dispersion 2 are given in Table 2 together with information concerning the heat pretreatment of Dispersion 2 and the sintering conditions used. The short circuit currents, I_{sc} , device parameters for the photovoltaic devices of reference Devices 2, 8 and 9 are also included in Table 2 by way of reference.

Table 2:

Device	TiO ₂ dispersion	Heat pre-treatment	Pretreatment temperature [°C]	Sintering conditions	Layer thickness (μm)	I_{sc} [mA/cm ²]
2(ref)	1	No	-	450°C	3.6	4.56
8(ref)	1	No	-	Pressure	2.5	2.58
9(ref)	1	No	-	Pressure	4.0	4.90
14(comp)	2	No	-	450°C	2.8	7.02
15(comp)	2	No	-	Pressure	3.1	0.96
16(comp)	2	Yes	450°C	450°C	2.6	6.68
17(inv)	2	Yes	450°C	Pressure	3.1	6.73

The results in Table 2 show that photovoltaic cells incorporating high temperature sintered titanium dioxide layers, as expected from the prior art, exhibited high short circuit currents, that prepared with Dispersion 2 without heat pretreatment exhibiting a much higher short circuit currents than those exhibited by photovoltaic cells incorporating high temperature sintered titanium dioxide layers prepared with Dispersion 1.

The results in Table 2 also show that for comparable titanium dioxide layer thicknesses the photovoltaic cell of Device 2 incorporating a high pressure sintered titanium dioxide layer prepared with Dispersion 1 exhibited a comparable short circuit current to that of Device 9 incorporating a high temperature

sintered titanium dioxide layer prepared with Dispersion 1, in accordance with the teaching of WO 00/72373.

However, if photovoltaic cells incorporated titanium layers prepared with Dispersion 2 without pretreatment, Device 15
5 incorporating a high pressure sintered layer exhibited a short circuit current which was much lower than that of Device 14 incorporating a high temperature sintered layer, at variance the teaching of WO 00/72373.

If, however, Dispersion 2 pretreated at 450°C was used,
10 according to the present invention, instead of Dispersion 2 without pretreatment, then short circuit currents comparable with that observed with Device 14 incorporating a high temperature sintered layer of Dispersion 2 without pretreatment were observed, whether high pressure sintering was used, as in the case of Device 17, or
15 high temperature sintering was used, as in the case of Device 16.

This demonstrates the advantage of the present invention in making it possible to realize high short circuit currents in photovoltaic devices incorporating a high temperature sintering layer of a metal oxide semiconductor nano-particle dispersion
20 prepared by a wet precipitation process, if the dispersion is subjected to prior thermal treatment.

iii) *Influence of titanium dioxide layer thickness on photovoltaic device performance:*

25

Table 3 gives the results obtained with further photovoltaic devices with front electrodes prepared with Dispersion 2 for different titanium dioxide layer thicknesses, together with information regarding the heat pretreatment and sintering
30 conditions. The short circuit currents, I_{sc} , device parameters for the photovoltaic devices of comparative Device 14 and invention device 17 are also included in Table 3 for the sake of comparison.

The results in Table 3 show that the short circuit current increased with titanium dioxide layer thickness for photovoltaic
35 devices incorporating high pressure sintered titanium dioxide layer prepared with Dispersion 2 with heat pretreatment, according to the present invention, and moreover that the short circuit currents for photovoltaic devices with high temperature sintered titanium dioxide layers prepared with Dispersion 2 with heat pretreatment
40 were comparable to those attained with photovoltaic devices incorporating high pressure sintered titanium dioxide layers at all titanium dioxide layer thicknesses.

Table 3:

Device	TiO ₂ dispersion	Heat pretreatment	Pretreatment temperature [°C]	Sintering conditions	Layer thickness (μm)	I _{sc} [mA/cm ²]
18 (comp)	2	No	-	450°C	2.6	7.24
19 (comp)	2	No	-	450°C	2.7	6.83
14 (comp)	2	No	-	450°C	2.8	7.02
20 (comp)	2	Yes	450°C	450°C	0.9	2.45
21 (comp)	2	Yes	450°C	450°C	1.0	2.51
22 (comp)	2	Yes	450°C	450°C	1.5	4.21
23 (comp)	2	Yes	450°C	450°C	1.5	4.42
24 (comp)	2	Yes	450°C	450°C	1.7	4.10
25 (comp)	2	Yes	450°C	450°C	1.8	5.17
26 (comp)	2	Yes	450°C	450°C	2.5	6.41
16 (comp)	2	Yes	450°C	450°C	2.6	6.68
27 (comp)	2	Yes	450°C	450°C	2.6	7.83
28 (comp)	2	Yes	450°C	450°C	3.8	7.00
29 (comp)	2	Yes	450°C	450°C	4.8	7.81
30 (inv)	2	Yes	450°C	Pressure	0.7	1.82
31 (inv)	2	Yes	450°C	Pressure	0.8	2.00
32 (inv)	2	Yes	450°C	Pressure	0.8	1.63
33 (inv)	2	Yes	450°C	Pressure	1.4	4.18
34 (inv)	2	Yes	450°C	Pressure	1.4	3.62
35 (inv)	2	Yes	450°C	Pressure	1.5	3.75
36 (inv)	2	Yes	450°C	Pressure	1.5	3.82
37 (inv)	2	Yes	450°C	Pressure	2.2	4.14
38 (inv)	2	Yes	450°C	Pressure	2.4	4.91
17 (inv)	2	Yes	450°C	Pressure	3.1	6.73

5 iv) Influence of the heat pretreatment temperature used for the titanium dioxide dispersion upon photovoltaic device performance:

The short circuit currents, I_{sc}, for photovoltaic devices with front electrodes incorporating sintered titanium dioxide layers
 10 prepared with Dispersion 3 sintered at different pretreatment temperatures are given in Table 4 together with information concerning the heat treatment of the Dispersion and of the sintering conditions used. The short circuit currents, I_{sc}, device parameters for the photovoltaic devices of comparative Devices 14
 15 and 15 are also included in Table 4 for the sake of comparison.

Table 4:

Device	TiO ₂ dispersion	Heat pretreatment	Pretreatment temperature [°C]	Sintering conditions	Layer thickness (μm)	I _{sc} [mA/cm ²]
14 (comp)	2	No	-	450°C	2.8	7.02
15 (comp)	2	No	-	pressure	3.1	0.96
39 (comp)	3	Yes	200	450°C	5.0	8.82
40 (inv)	3	Yes	200	pressure	4.5	1.07
41 (comp)	3	Yes	350	450°C	1.7	4.10
42 (inv)	3	Yes	350	pressure	2.2	4.14
43 (comp)	3	Yes	400	450°C	1.5	3.82
44 (inv)	3	Yes	400	pressure	2.2	4.89
45 (comp)	3	Yes	450	450°C	1.6	3.51
46 (inv)	3	Yes	450	pressure	1.8	2.77
47 (inv)	3	Yes	450	pressure	2.0	2.50
48 (inv)	3	Yes	450	pressure	2.2	2.54
49 (inv)	3	Yes	450	pressure	2.4	2.85

The results in Table 4 show that the short circuit current of photovoltaic devices incorporating a high pressure sintered titanium dioxide layer prepared with Dispersion 3 with heat pretreatment, according to the present invention, are comparable with the short circuit current of photovoltaic devices incorporating a high temperature sintered titanium dioxide layer prepared with Dispersion 3 with the same heat pretreatment for pretreatment temperatures of 350 and 400°C, see the results for Devices 42 and 44 versus Devices 41 and 43.

The short circuit currents of a photovoltaic devices incorporating a high pressure sintered titanium dioxide layer prepared with Dispersion 3 heat pretreated at 450°C, Devices 46-49, were slightly below that of Device 45 incorporating a titanium dioxide layer prepared with Dispersion 3 with the heat pretreatment at 450°C and sintered at 450°C.

Furthermore, the short circuit current of a photovoltaic device incorporating a high pressure sintered titanium dioxide layer prepared with Dispersion 3 with heat pretreatment at 200°C, Device 40, was significantly below the short circuit current of that of Device 39 incorporating a high temperature sintered titanium dioxide layer prepared with Dispersion 3 with heat pretreatment at 200°C.

EXAMPLE 2

Low temperature heat treatment after high pressure sintering

5 Photovoltaic devices were prepared as described for Device numbers 46 to 49 except that the titanium dioxide layer thicknesses were different and that after sintering the titanium dioxide layers were heated for 5 minutes at 150°C before drying. The short circuit currents obtained with these devices, Devices 50 to 52, together
10 with details over their titanium dioxide layer thickness and processing are given in Table 5 together with the results for Devices 46 to 49.

Table 5:

15

Device	TiO ₂ dispersion	Heat pre-treatment at 450°C	Sintering conditions	Post-pressure sintering heating temperature [°C]	Layer thickness (µm)	I _{sc} [mA/cm ²]
46(inv)	3	Yes	pressure	-	1.8	2.77
47(inv)	3	Yes	pressure	-	2.0	2.50
48(inv)	3	Yes	pressure	-	2.2	2.54
49(inv)	3	Yes	pressure	-	2.4	2.85
50(inv)	3	Yes	pressure	150	0.9	2.05
51(inv)	3	Yes	pressure	150	1.1	2.53
52(inv)	3	Yes	pressure	150	1.4	3.03

Taking into account the increase in short-circuit current with increasing titanium dioxide layer thickness, it is clear that post-pressure sintering heating at moderate temperatures increased the
20 short-circuit current observed.

The present invention may include any feature or combination of features disclosed herein either implicitly or explicitly or any
25 generalisation thereof irrespective of whether it relates to the presently claimed invention. In view of the foregoing description it will be evident to a person skilled in the art that various modifications may be made within the scope of the invention.

CLAIMS

1. A process for preparing a layer of a nano-porous metal oxide semiconductor comprising the steps of: (i) providing metal
5 oxide semiconductor nano-particles prepared by a wet precipitation process, (ii) heating said nano-particles at a temperature in the range of 250 to 600°C, (iii) preparing a dispersion of said heat-treated nano-particles from step (ii), (iv) applying said dispersion prepared in step (iii) to a
10 support to produce a coating; and (v) subjecting said coating to a pressure in the range of 100 to 1000 bar at a temperature below 250°C.
2. Process according to claim 1, wherein said metal oxide is
15 selected from the group consisting of titanium oxides, tin oxides, niobium oxides, tantalum oxides, tungsten oxides and zinc oxides.
3. Process according to claim 1, wherein said pretreatment
20 temperature is in the range of 300 to 500°C.
4. Process according to claim 1, wherein said sintering pressure is in the range 400 to 600 bar.
- 25 5. Process according to claim 1, wherein the process further comprises heating said coating subjected to pressure from step (v) at a temperature of 100 to 200°C.
6. Process according to claim 1, wherein said nano-porous metal
30 oxide semiconductor has a band-gap of greater than 2.9 eV.
7. Process according to claim 1, wherein said nano-porous metal oxide nano-particles have a mean number averaged particle size ≤ 20 nm.
35
8. A layer of a nano-porous metal oxide semiconductor obtainable by a process for preparing a layer of a nano-porous metal oxide semiconductor comprising the steps of: (i) providing metal oxide semiconductor nano-particles prepared by a wet
40 precipitation process, (ii) heating said nano-particles at a temperature in the range of 250 to 600°C, (iii) preparing a dispersion of said heat-treated nano-particles from step (ii),

(iv) applying said dispersion prepared in step (iii) to a support to produce a coating; and (v) subjecting said coating to a pressure in the range of 100 to 1000 bar at a temperature between 20 and 250°C.

5

9. Layer according to claim 8, wherein said layer contains at least one spectral sensitizer for the nano-porous metal oxide semiconductor selected from the group consisting of metal chalcogenide nano-particles with a band-gap between 1.5 and 2.9 eV, organic dyes, and metallo-organic dyes.
10. A photovoltaic device comprising a layer of a nano-porous metal oxide semiconductor obtainable by a process for preparing a layer of a nano-porous metal oxide semiconductor comprising the steps of: (i) providing metal oxide semiconductor nano-particles prepared by a wet precipitation process, (ii) heating said nano-particles at a temperature in the range of 250 to 600°C, (iii) preparing a dispersion of said heat-treated nano-particles from step (ii), (iv) applying said dispersion prepared in step (iii) to a support to produce a coating; and (v) subjecting said coating to a pressure in the range of 100 to 1000 bar at a temperature below 250°C.

INTERNATIONAL SEARCH REPORT

International Application No

PCT/EP 02/10270

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H01G9/20 H01L51/20

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 H01G H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, INSPEC, WPI Data, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	BARBE C J ET AL: "MESOPOROUS TiO2 ELECTRODES FOR PHOTOVOLTAIC APPLICATIONS" MATERIALS RESEARCH SOCIETY SYMPOSIUM PROCEEDINGS, MATERIALS RESEARCH SOCIETY, PITTSBURG, PA, US, vol. 431, 11 April 1996 (1996-04-11), pages 129-134, XP001025709 ISSN: 0272-9172 the whole document	1,2,4, 6-10
Y	WO 00 72373 A (LINDQUIST STEN ERIC ;LINDSTROEM HENRIK (SE); HAGFELDT ANDERS (SE);) 30 November 2000 (2000-11-30) cited in the application page 5, line 23 -page 10, line 31; claims 1-8; figures 1-5	1,2,4, 6-10

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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- *&* document member of the same patent family

Date of the actual completion of the international search

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INTERNATIONAL SEARCH REPORT

International Application No

PCT/EP 02/10270

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

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A	P.M. SOMMERLING ET AL.: "Flexible dye-sensitized nanocrystalline TiO ₂ solar cells" 16TH EUROPEAN PHOTOVOLTAIC SOLAR ENERGY CONFERENCE, 1 - 5 May 2000, pages 67-71, XP001138243 Glasgow, UK the whole document ---	1-3,6-10
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International Application No
PCT/EP 02/10270

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