

ADVANCED SOLID ELECTROLYTE AND METHOD OF FABRICATION

Field of the invention

5 The present invention generally relates to a fabrication method of layer of solid electrolyte material which is in particular interesting for applications as for instance electrochemical conversion devices or sensors, in particular a solid oxide fuel cell and oxygen sensors.

Background of the invention

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General concerns about global warming have initiated many studies in order to find alternative solutions with respect to the utilization of fossil fuels, one of which has been the development of the so called solid oxide fuel cell (SOFC). Industrial scale production of high power fuel cells remains
15 uncertain essentially due to the high production costs and limited life time of these devices. The high production costs are due to time consuming manufacturing techniques while limited life time is linked to the high working temperature of the cells. Such high working temperatures are necessary in order to achieve high ionic conductivity of the materials used as solid
20 electrolyte as the ionic conductivity is a temperature dependent materials parameter. The main actual trends in research are directed to the developments of solid electrolyte layers with higher ionic conductivity and/or lower thickness in order to be able to reduce the working temperature of the cells. However, the thickness of the solid electrolyte layer has to be chosen
25 with respect to the material quality, in particular in order to avoid electrical shortcuts (for applications for which such a parameter is important) and/or maintain gas tightness which are limiting factors, both of which in particular for SOFC. Further for low thickness the uniformity of the thickness is highly
30 affected due to the polycrystalline morphology of certain materials commonly used as electrolyte for SOFC. The grain size represents a lower limit for the thickness below which the materials properties might change and cannot be guaranteed anymore.

A recent review published in *Advances in Manufacturing*, Vol. 2, Issue 3, pp 212-221, describes recent efforts obtained using thermal spray techniques and physical vapour deposition (PVD) techniques for SOFC electrolyte layer manufacturing.

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For what concerns thermal spraying, developments have been made with regards to the spraying parameters as well as post processing of the deposited layers but none of these developments were able to provide solid electrolyte layers with a thickness below 10 μm nor has been able to achieve high ionic conductivity compared to high quality bulk material, as for example for yttria stabilized zirconia (YSZ).

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PVD has normally the advantage that thin films with rather high stoichiometric quality can be produced, but in the context of SOFC the application of PVD is difficult due to the high porosity of the electrode materials acting as growth substrates which is prerequisite of such cells. This impact on material quality influences the already rather low mechanical stability of such PVD solid electrolyte layers. Similar problems are encountered for other thin film deposition techniques as for instance pulsed laser deposition, see for instance *Journal of Physics: Conference Series* 59, 2007, 140-143. Large area deposition of YSZ films with thickness in the range of 300 nm up to 1200 nm have been obtained over areas as large as 50-100 cm^2 , but such results are only possible on non-porous substrates, for example Si in case of YSZ layers deposited by pulsed layer deposition.

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The above mentioned problems apply to all applications which would involve an electrolyte material in solid form and, thus, the present invention is not limited to the above depicted cases. For instance, the present invention is also related to oxygen sensors, in particular like those based on a working principle also called Nernst cell, where a solid electrolyte layer is sandwiched in between two metal electrodes, in particular made of platinum.

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The present invention could also be applicable to other fields, as for instance Li-ion batteries.

5 The objective of the invention is to propose a fabrication method of a layer of solid electrolyte material which is in particular interesting for applications as for instance electrochemical conversion devices or sensors, in particular a solid oxide fuel cell and oxygen sensors, obviating the above-mentioned detriments. Another objective is to propose a fabrication method of devices and devices comprising such a layer of solid electrolyte. In particular,
10 applications as for instance Li-ion or Na-ion or H-ion batteries, non-oxygen chemical sensors, air separation units, solid oxide electrolyser cells (SOEC) can be envisaged. Further another objective is to propose a structure donor substrate which allows multiple transfer of solid electrolyte material.

15 Description of the invention

The present invention relates to a method of providing a layer of solid electrolyte by a layer transfer technique from a host substrate.

20 In particular the present invention relates to a method of manufacturing a device comprising a solid electrolyte layer, characterized that it comprises providing a host substrate including a crystalline solid electrolyte layer, and transferring said crystalline solid electrolyte layer from the host substrate to a receiver substrate.

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Further advantageous embodiments relate to a method of providing a layer of solid electrolyte characterized in that the host substrate comprises either a bulk substrate of crystalline solid electrolyte material or a donor layer of crystalline solid electrolyte provided on a support substrate.

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Further advantageous embodiments relate to a method of providing a layer of solid electrolyte characterized in that the donor layer of solid electrolyte is provided on the support substrate by a deposition technique, in particular chemical vapor deposition, or, independently, by a second layer transfer
5 technique similar to the one already outlined from another donor substrate.

Further advantageous embodiments relate to a method of providing a layer of solid electrolyte wherein the layer transfer technique comprises a step of assembling the host substrate to a receiver substrate, the solid electrolyte
10 layer being between said substrates, and a step of thinning the host substrate.

Further advantageous embodiments relate to a method of providing a layer of solid electrolyte wherein the step of thinning comprises a step of formation
15 of a zone of weakness in the host substrate so as to define a portion of the host substrate comprising the layer to be transferred and a step of detaching at the zone of weakness so as to transfer said portion to the receiver substrate.

20 Further advantageous embodiments relate to a method of providing a layer of solid electrolyte wherein the step of formation of a zone of weakness is obtained by implantation of atomic and/or ionic species.

Further advantageous embodiments relate to a method of providing a layer
25 of solid electrolyte wherein the step of formation of a zone of weakness comprises formation of a release layer in the host substrate, said release layer being activated during the step of detaching in a way that detaching occurs

30 Further advantageous embodiments relate to a method of providing a layer of solid electrolyte wherein the detaching step is obtained by at least one of:

annealing, application of thermal stress, application of mechanic stress, application of irradiative means, in particular a laser beam, and etching.

Further advantageous embodiments relate to a method of providing a layer
5 of solid electrolyte wherein the solid electrolyte material has ionic conductivity, in particular for hydrogen, oxygen, lithium or sodium ions, above 0.01 S/cm.

This is particularly advantageous in order to be able to decrease the
10 operating temperature of certain device applications as for instance SOFC, as the ionic conductivity is a temperature dependent parameter. The present invention allows adaption of the materials properties of the electrolyte layer in order to be able to tune such parameters, for instance the ionic conductivity reaching a certain predetermined value at any wished
15 temperature. Thus even at operating temperature below 600°C, more preferentially below 450°C, one is able to obtain high ionic conductivity of above 0,01 S/cm.

Further advantageous embodiments relate to a method of providing a layer
20 of solid electrolyte wherein the layer of solid electrolyte has a thickness in the range of 10 nm up to 100 µm with a variation in thickness below 5%, more preferentially below 1%.

Further advantageous embodiments relate to a method of providing a layer
25 of solid electrolyte wherein the layer of solid electrolyte has a defect density below a predetermined level, in particular lower than 5/cm².

Further advantageous embodiments relate to a method of providing a layer
30 of solid electrolyte wherein the layer of solid electrolyte is a monocrystalline layer.

Further advantageous embodiments relate to a method of providing a layer of solid electrolyte wherein the material of the solid electrolyte layer is a perovskite material and/or is chosen among the group of zirconia, ceria, gallates, alumina.

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Further advantageous embodiments relate to a method of providing a layer of solid electrolyte wherein after transfer of the solid electrolyte layer onto the receiver substrate, there remains a portion of the host substrate which is further useable as host substrate for a subsequent transfer of a solid electrolyte layer.

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Further the present invention also relates to a device, in particular chemical sensor, fuel cell, electrolyser, gas separation unit, or battery, comprising a layer of solid electrolyte obtained by transferring as claimed by the present invention.

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Further the present invention also relates to a method of fabrication of a solid oxide fuel cell comprising an anode, a cathode, a layer of solid electrolyte in between said anode and cathode, and electrodes on the side of the anode and the cathode opposing to the layer of solid electrolyte, comprising carrying out the method according to the present invention for transferring a crystalline solid electrolyte layer onto the anode and/or the cathode.

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Further the present invention also relates to a method of fabrication of an oxygen sensor comprising two electrodes and a layer of solid electrolyte in between said two electrodes comprising carrying out the method according to the present invention for transferring a crystalline solid electrolyte layer onto the anode and/or the cathode.

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Further the present invention also relates to a method of fabrication of a battery comprising an anode, a cathode, a layer of solid electrolyte in between said anode and cathode, and electrodes on the side of the anode and the cathode opposing to the layer of solid electrolyte, comprising
5 carrying out the method according to the present invention for transferring a crystalline solid electrolyte layer onto the anode and/or the cathode.

Further the present invention also relates to a method of fabrication of a donor structure comprising a donor substrate having a main surface and a
10 plurality of crystalline solid electrolyte layer portions on said main surface, wherein each of the plurality of crystalline electrolyte layer portions is obtained by the method according to the present invention for transferring a crystalline solid electrolyte layer onto the main surface of the donor substrate.

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This method of fabrication has the advantage that it opens up the way to the possibility to provide high quality solid electrolyte material layers with well defined properties as for instance very good thickness uniformity, high ionic
20 conductivity, and very good electrically insulating properties and that down to very low thickness of the layer.

The method also gives more flexibility with respect to existing fabrication methods because the materials properties of the transferred layer can be
25 tuned independently, and in particular these properties would not depend on the electrode materials properties (morphology, porosity, defect or dislocation density) as the electrolyte is not directly grown on the electrode. The interface properties, in particular already improved for molecular or direct bonding, are further enhanced due to the possibility of adapted
30 surface treatments on both the electrode and the electrolyte layer, in

particular with respect to the roughness or also the chemical surface termination of these layers.

The invention will be described in more detail by way of example hereinafter using advantageous embodiments and with reference to the drawings. The described embodiments are only possible configurations in which the individual features may, however, be implemented independently of each other or may be omitted. Similar elements illustrated in the drawings are provided with the same reference sign. For steps, an additional S at the beginning is added. Parts of the description relating to equal elements or steps illustrated in the different drawings may be left out.

Figure 1A schematically illustrates a method for providing a layer of solid electrolyte by a layer transfer technique in accordance with embodiments of the present invention.

Figure 1B, 1C, and 1D schematically illustrates a host substrate for a method for providing a layer of solid electrolyte by a layer transfer technique in accordance with embodiments of the present invention.

Figure 2 schematically illustrates a method for providing a layer of solid electrolyte by a layer transfer technique in accordance with embodiments of the present invention.

Figures 3A, 3B, and 4 schematically illustrates the formation of a zone of weakness for a method for providing a layer of solid electrolyte by a layer transfer technique in accordance with embodiments of the present invention.

Figure 5 schematically illustrates an electrochemical conversion device in accordance with embodiments of the present invention.

Figure 6 schematically illustrates an electrochemical conversion sensor in accordance with embodiments of the present invention.

Figure 7 schematically illustrates a donor structure or also called structured donor substrate in accordance with embodiments of the present invention.

The present invention will now be described with reference to specific embodiments. It will be apparent to the skilled person that features and alternatives from any of the embodiments can be combined, independently of each other, with features and alternatives of any other embodiment in accordance with the scope of the claims.

Figure 1A schematically shows a method for providing a layer of solid electrolyte 111 by a layer transfer technique S11 in accordance with embodiments of the present invention. It is schematically indicated that the layer of solid electrolyte 111 is separated from a host substrate 100, thus leaving behind a remaining host substrate 100'. It will become clear from the discussion below regarding various embodiments of the present invention in which way the layer of solid electrolyte 111 may be comprised in the host substrate 100 and in which way the layer of solid electrolyte 111 is separated.

Figure 1B schematically shows a host substrate 100 which is entirely formed by a bulk substrate 101. It is also schematically indicated a donor layer of solid electrolyte 110 which is present close to one face of the host substrate 100. It will become clear from the description below in which way such a donor layer of solid electrolyte 110 can be defined in the host substrate 100.

Figure 1C schematically shows a host substrate 100 which comprises a support substrate 102 on which is provided a donor layer of solid electrolyte 110. Such a donor layer of solid electrolyte 110 might be obtained by several techniques as for instance, but not limited to, pulsed laser deposition, physical vapour deposition, chemical vapour deposition, spray coating, evaporation, sputtering, or atomic layer deposition. The choices of the support substrate 102 as well as the growth technique directly influence the materials properties of the donor layer of solid electrolyte 110 and these properties can be well adjusted depending on the envisaged application.

Figure 1D schematically shows a host substrate 100 which comprises a support substrate 202 on which is provided a donor layer of solid electrolyte 210 by a layer transfer technique S11 from a donor substrate 200 as claimed by the present invention. This gives the opportunity and flexibility to take into account the preparation of both faces of the layer of solid electrolyte 111, obtained by layer transfer technique in accordance with the present invention from the respective donor layer of solid electrolyte 210, by surface treatments or thermal treatments for which the initial donor substrate would not have been suitable before integration of the layer of solid electrolyte 111 in its final stack of layers or device.

Materials of choice for the solid electrolyte are doped (dopant X) zirconia-based materials ($\text{ZrO}_2\text{-X}$). As dopants a large number of divalent and trivalent metal oxides (Y_2O_3 , Yb_2O_3 , Sc_2O_3 , CaO , MgO , etc.) may be selected. In an advantageous embodiment the monocrystalline phase of such materials is preferred due to higher crystalline quality and lower defect density with respect to the polycrystalline phase. The grains of the latter, in turn, stabilize the high temperature tetragonal or cubic phase to room temperature. In particular in the $\text{ZrO}_2\text{-Y}_2\text{O}_3$ system, 2.5 mol% Y_2O_3 stabilizes the tetragonal (t) and 8.5 mol% Y_2O_3 the cubic (c) phase at 1000°C. The tetragonal phase is usually found as a small grain (0.5 μm) material with high mechanical strength, toughness and thermal shock resistance, and an ionic conductivity of 0.055 Scm^{-1} at 1000°C. In comparison, the large grained cubic phase has lower strength (at RT) but a conductivity of around 0.15 Scm^{-1} at 1000°C. In case of polycrystalline material one should note that an advantageous embodiment could consist in texturing the material, that is to align the orientation of the grains with respect to the surface which is advantageous because of a better homogeneity of the material, a better control of the thickness uniformity and roughness, as well as a better reproducibility on a manufacturing perspective. However monocrystalline

material is preferably used. In polycrystalline materials the thickness should be chosen preferentially higher than the average grain size in order to ensure an overall dense material.

- 5 However, the present invention is not limited to these kind of materials, and one could envisage other materials as for instance $\text{BaY}_{0.2}\text{Zr}_{0.8}\text{O}_{3-\delta}$ or doped (CaO , Y_2O_3 , Sm_2O_3 , Gd_2O_3) ceria-based materials, in particular Gadolinia-doped ceria, or for instance known perovskite-based lanthanum gallate doped with strontium and magnesium (LSGM). One should note that ceria-
10 based materials would suffer oxygen loss and need to be protected on the anode side. Further it should be noted that LSGM for instance is incompatible with certain anode materials likely used for SOFC as for instance NiO . Such materials deficiencies and incompatibilities indicate that an alternative fabrication method is required which is able to counteract such
15 problematic. For the present invention this is the providing of a suitable protective coating situated between the anode and the ceria-based materials or the LSGM and certain anode materials.

The possibility to use either bulk substrates 101 or providing a donor layer of
20 solid electrolyte 110 on a support substrate 102 independent on constraints directly imposed by growth on materials used in the final device offers an outstanding flexibility in design and quality of the layer of solid electrolyte 111 integrated in the final device. It is thus possible to keep the defect density in such layer of solid electrolyte 111 below $5/\text{cm}^2$, the thickness
25 below $2\text{ }\mu\text{m}$ while achieving a thickness uniformity better than 5%, and that even in case of polycrystalline materials. Ionic conductivity values as high as 0.01 S/cm , in particular while maintaining a good insulating behavior for electrons and a high gas tightness for involved gas species.

- 30 Figure 2 schematically shows the assembling step S2 of host substrate 100 comprising a donor layer of solid electrolyte 110 with a receiver substrate

203 and a step of thinning S3 of the assembled structure leading to a layer of solid electrolyte 111 remaining on the receiver substrate 203. The assembling step S2 can be obtained by any bonding technique as for instance direct bonding, thermocompression bonding, eutectic bonding, ceramic mediated bonding, or any other known technique suitable. A direct bonding is preferred as it provides long term stability of the bond and a defect free bonding interface showing good electrochemical behavior, in particular high ionic conductivity and low electrical conductivity. Prior to the step of assembling S2 the surface of the receiver substrate 203 as well as the donor layer of solid electrolyte 110 may be prepared, for instance by a step of, or a combination of steps of etching, grinding, polishing, in particular chemical mechanical polishing, or any other surface treatment technique, or even thermal treatment, in order to decrease the roughness of the surface and/or the number of defects present at the surface. The thinning step S3 schematically displayed in Figure 2 might be obtained by several techniques some of which will be described below in more detail. For instance the step of thinning S3 might be obtained by a combination of grinding and subsequent etching of the host substrate 100 which might be interesting if the material of the host substrate 100 is rather cheap and highly available so that such a sacrificial step would be cost efficient with respect to industrialization. Other possibilities of the step of thinning S3 might be the fracture along a zone of weakness 320, for instance obtained by implantation of ionic and/or atomic species or for instance obtained by the introduction of a buried liftoff layer 330 selectively sensitive to etching, defining thus a donor layer of solid electrolyte 110 which can be transferred to the receiver substrate 203. Other possibilities of the step of assembling S2 might be providing the receiver substrate 203 by a deposition sequence whereby any technique of deposition, like vapor phase or liquid phase deposition, sputtering, evaporation, spray deposition, spin coating for instance.

Figure 3A schematically refers to the case shown in Figure 1B of a host substrate 100 formed entirely by a bulk substrate 101, and shows the step of formation S4 of a zone of weakness 320 by implantation of ionic and/or atomic species, in particular H or He or a combination thereof, through one face of the host substrate 100, thereby defining the donor layer of solid electrolyte 110. In Figure 3B similar technical aspects are schematically shown which, however, refer to the cases shown in Figures 1C and 1D where a donor layer of solid electrolyte 110 or 210 is provided on a host substrate 102 or 202, respectively. As such a donor layer of solid electrolyte 110 might be not of same material as the support substrate 102 or 202, the zone of weakness 320 can be either formed in the donor layer of solid electrolyte 110 or 210 or in the support substrate 102 or 202, or in-between in an intermediate layer.

Typically, implantation is realized in a range of implantation energies from 50 keV to 1 MeV with an implantation dose ranging typically from 2×10^{16} to 12×10^{17} H⁺/cm² in case of H⁺ ions (and/or He ions) which permits to define a zone of weakness 320 at a depth of about 0.2 to 10 μm below the implanted surface.

Figure 4 schematically shows another advantageous embodiment with respect to the step of thinning S3 depicted in Figure 2. Figure 4 shows a host substrate 100 comprising a support substrate 102 or 202 and a donor layer of solid electrolyte 110 or 210, in between of which a release layer, often also called liftoff layer, 330 is formed which acts as a zone of weakness 320 for the step of thinning S3. Such a liftoff layer 330 might be introduced either during the growth of the donor layer of solid electrolyte 110 on the support substrate as described with regard to the embodiment schematically shown in Figure 1C, or during the layer transfer technique S11 as schematically shown in Figure 1D whereby the liftoff layer 330 is provided

on the support substrate or the layer to be transferred prior to the transfer, or a combination thereof.

After assembling the host substrate 100 (of Figure 3A, 3B, or 4) with the receiver substrate 203 as shown in Figure 2, the step of thinning S3 with respect to the formed zone of weakness 320 can be performed by annealing or by application of thermal and/or mechanical stress, for instance a thermal treatment realized in the range of 200°C to 900 °C for a duration ranging from seconds to hours might induce fracture at the zone of weakness 320, allowing thus a step of detachment S5 to occur. The insertion of a blade can act as application of mechanical stress. Other possibilities might be a step of detaching S5 by application of irradiative means, in particular a laser beam. This could be achieved by a change in the absorption occurring by the presence of the implanted species at the zone of weakness and application of a laser beam tuned to this selective peak in absorption. Another possibility could be a selective absorption in the liftoff layer 330 which dissociates under such selected irradiation. Preferentially the rest of the host substrate 100 is substantially transparent to such irradiation, and even more preferentially, the rest of the host substrate 100 as well as the layer of solid electrolyte are protected from eventually occurring heat dissipation in the region of the liftoff layer 330 during such irradiation, for instance by presence of thermal diffusion barrier layers in between the liftoff layer 330 and the adjacent layers. Another possibility for the step of detaching S5 is the application of a selective etch solution to the zone of weakness, easily achievable by an adequate choice of material for the liftoff layer 330 for instance.

The main advantage of the layer transfer technique S11 involving a step S4 of formation of a zone of weakness and a detaching step S5 is the possibility to reuse the remaining host substrate 100' for further fabrication. This is especially noteworthy whenever the cost of such substrates is rather high.

After a rather simple surface treatment, for instance chemical mechanical polishing but not limited to it, of the remaining host substrate 100' the latter can be reused as host substrate 100 or support substrate 102 according to the present invention. However one can also imagine a scenario in which the material of the host substrate 100 is rather cheap, and reuse is not of real economic interest. In such a configuration the thinning step S3 can be equivalent to the removal of the host substrate by any conventional thinning technique (etching, grinding, or polishing).

Further advantageous embodiments might comprise multiple transfers. One embodiment is thereby related to subsequently performed layer transfer from the same host substrate 100. This is advantageous whenever a donor layer of solid electrolyte 110 can be provided as a rather thick layer while maintaining the suitable high quality. Surface treatments after a layer transfer on the remaining host substrate 100' might be crucial in order to optimize the remaining host substrate 100' for subsequently performed transfer of another layer of solid electrolyte according to the present invention.

Another embodiment is related to the use of an intermediate handling substrate. From the host substrate 100 the layer of solid electrolyte 111 is transferred to an intermediate handling substrate which itself can act subsequently as new host substrate. This is schematically indicated in Figure 1D. This is advantageous whenever for instance the crystallographic termination of the layer of solid electrolyte 111 is different on both sides of said layer which might play a role. A transfer from the intermediate handling substrate to the receiver substrate 203 does thus not change such termination or orientation, allowing further optimization and giving much more flexibility in the materials choice. Other reasons can justify the use of an intermediate handling substrate. For instance, as it allows to de-correlate the step of detaching the electrolyte layer from its original host substrate and

the step of assembling it on the final support substrate, more flexible process windows can be obtained. Another reason would be to allow for more flexibility regarding surface treatments of the electrolyte layer, and this for both of its two faces.

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Figure 5 schematically illustrates an electrochemical conversion device 510 comprising contact structures 503, an anode 501, a cathode 502, and a layer of solid electrolyte 111 arranged in between said anode 501 and cathode 502. As already mentioned before, the electrochemical conversion
 10 device 510 is not limited to the application of SOFC wherein a layer of solid electrolyte 111 is used, but may also be related to similar systems as for instance Li-ion batteries. In case of SOFC the contact structures 503 not only provide electronic conduction but also comprise means of transport of gas from fuel, whereas in Li-ion batteries essentially electronic conduction is
 15 necessary as the ions are transported from anode to cathode and intercalated therein and vice-versa due to the electrochemical potential difference but no reduction or oxidation process occurs leading to or using volatile species as oxygen or hydrogen.

20 Depending on the application the materials involved are chosen appropriately. In case of SOFC, the anode materials might be chosen among porous Ni-YSZ cermet, Cu-YSZ cermet, strontium titanate or others commonly known, whereas cathode materials might be chosen among perovskite-based LaMnO_3 accompanied by a ceria-based interlayer to
 25 assure chemical stability versus YSZ electrolyte material. Other materials for the cathode as for instance $\text{La}_{0.8}\text{Sr}_{0.2}\text{MnO}_3$ (LSM) or $\text{La}_{0.5}\text{Sr}_{0.5}\text{CoO}_3$ or $\text{Ln}_{1.6}\text{Sr}_{0.4}\text{Co}_{1-y}\text{Fe}_y\text{O}_{3-\delta}$ (LSCF, where $\text{Ln} = \text{La, Sm, Nd, Gd, Dy}$) or $\text{Ba}_{1-x}\text{Sr}_x\text{Co}_{1-y}\text{Fe}_y\text{O}_{3-\delta}$ (BSCF) can be chosen.

In case of Li based batteries, the solid electrolyte material of choice is LiPON or Li_3PO_4 , anode and cathode materials might be chosen of those well known in the art, as for instance LiCO_2 , Li, TiOS.

- 5 Further illustration is given in an exemplary manner for embodiments in relation with Figure 5. However the present invention is not limited to such exemple, and technical aspects are of interest for other applications. In relation with Figure 5, a classical architecture well-known for SOFC is presented, with an anode 501 made of NiO-YSZ, a cathode 502 made of
10 LSM, and a layer of solid electrolyte 111 made of monocrystalline YSZ. Standard electrodes are used as contact structures 503.

The process starts by providing the anode 501 by commonly known techniques as for instance sintering. Optionally the anode is supplied with its
15 electrode already formed, or the corresponding electrode can be formed later in the process. Advantageously a planarization step is performed on the anode 501 in order to provide a surface having low roughness, in particular below 0.6nm rms as measured by Atomic Force Microscopy (AFM), which is much more suitable for the assembling step via bonding techniques.
20 However, one might alternatively provide a planarization layer and/or bonding layers as discussed elsewhere in the specification.

The host substrate 100 from which the layer of solid electrolyte 111 is obtained is made of YSZ in a monocrystalline phase, for instance of square
25 form with dimensions of 20 x 20 mm. Implantation of hydrogen H^+ is performed on the monocrystalline YSZ in order to obtain the zone of weakness 320 necessary for a subsequent transfer by splitting. Typically such implantation is performed using implantation energies ranging from 50 keV to 1 MeV, implantation doses ranging from $2 \text{ E}+16/\text{cm}^2$ to $1.2\text{E}+17/\text{cm}^2$,
30 which lead to a zone of weakness 320 separating the donor layer of solid

electrolyte 110 having a thickness, which thus depends on the exact implantation parameters, ranging from 0.2 to 10 μm .

After the assembly of the donor layer of solid electrolyte 110 to the anode 501, splitting at the zone of weakness 320 is provided by a thermal treatment with temperatures ranging from 300°C to 1000°C for a duration ranging from seconds to hours depending on the temperature of the anneal. After transfer obtained by such splitting, an optional planarization step on the transferred layer might be suitable for the subsequent providing of the cathode 502. The LSM cathode material might be directly deposited on the transferred layer by any known deposition means, like tape casting, sintering, vapor phase or liquid phase deposition, sputtering, evaporation, sintering, spray coating, sol-gel technique, serigraphy etc., or one could assemble with a separately provided cathode by above mentioned bonding and/or transfer techniques applied to the cathode. For instance assembly could be obtained by lamination or direct bonding of a LSM substrate on the above mentioned planarized YSZ layer which has been transferred on the anode according to embodiments of the present invention. A thermal treatment with temperatures ranging from 500°C to 1400°C with a duration ranging from seconds to hours depending on the temperature of the anneal can optionally be performed in order to increase the overall mechanical stability of the assembled structure. Finally metal electrodes are provided on both anode (if not already formed) and cathode side by techniques commonly known.

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The method of providing a layer of solid electrolyte 111 according to embodiments of the present invention has the advantage that said method can be used to avoid incompatibilities of the material chosen for the layer of solid electrolyte 111 and the materials chosen for the anode 501 or cathode 502.

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One type of incompatibility might be based on that said anode 501 and cathode 502 have a certain type of material and morphology, for instance a high porosity, in order to allow optimized performance in the chosen application. For instance high porosity is chosen in case of SOFC in order to
5 allow penetration of oxygen or hydrogen in the respective material layer, and also to increase the ionic conductivity of the respective ions to the layer of electrolyte material. However such a rather inhomogeneous morphology negatively impacts layers that would have been grown upon such anode or cathode material and, thus, does not allow high quality, for instance
10 monocrystallinity, and low defect densities as claimed by the present invention.

Other incompatibilities concern thermal budget applied during growth or deposition of certain layers which may have detrimental effects as diffusion
15 or phase changes in the underlying structure.

Also the flexibility in the fabrication method of such electrochemical conversion devices 510 is increased as the layer of solid electrolyte 111 may be provided on either the anode 501 or the cathode 502. Prior to such
20 assembly the layer of solid electrolyte 111 and the other structure may undergo treatments in order to improve the interface after assembly, as for instance polishing in order to decrease the roughness, making it more suitable for instance for a bonding process, in particular direct bonding. Further it is also possible to provide bonding layers and/or planarizing layers
25 before assembly on the layer of solid electrolyte 111 and/or the other structure in order to provide better bonding quality.

For instance the layer of solid electrolyte 111 may be provided on the anode 501, but similar reasoning would apply to a provision on the cathode 502.
30 Thermal treatments after or during the assembly might be necessary in order to ensure the mechanical integrity of the assembled structure, with

temperature ranging from 500°C up to 1400°C and treatment duration ranging from seconds to hours depending on the temperature of the anneal. Subsequently one has either the choice to assemble a structure comprising the cathode 502 and its contact structure 503 to the free face of the layer of solid electrolyte 111. Or one has the choice to grow the respective cathode 502 and its contact structure 503 on the free face of the layer of solid electrolyte 111 if no incompatibilities between the growth or deposition technique, as for instance a too high thermal budget applied during such growth for the other counterpart, exists. Such flexibility also shows by the fact that each of the constituent parts of the electrochemical conversion device 510 can be subjected to its proper individual treatment, for instance thermal annealing, chemical treatment, diffusion doping, prior to the assembling with the other constituent parts of the electrochemical conversion device 510. Anode 501 and cathode 502 for instance can thus be optimized in terms of catalytic activity for oxygen dissociation and incorporation reactions in cathode 502 and for electrochemical oxidation of H₂ or CO and other fuel processing in anode 501. Further the electronic conductivity of both anode 501 and cathode 502 may be increased due to the flexibility in treatments; the same applies to the chemical and mechanical stability with respect to the other constituents. For instance an alignment of CTE (coefficient of thermal expansion) throughout the electrochemical conversion device 510 might be of interest in order to increase the mechanical stability and, thus, lifetime of the device at the high operating temperature. Such an attunement of CTE might be obtained by the choice of the material. Thus an overall optimized device is obtained.

As described above the present invention is related to applications involving a layer of solid electrolyte, as for instance SOFC which is related to generate electricity (and heat) by the input of combustibles or fuels like for instance hydrogen and oxygen. It becomes immediately clear that the inverse functionality, that is the generation of combustibles by use of electricity and

electrolysis, is possible using the same configuration and, thus, all descriptive elements of the specifications apply, as schematically shown in Figure 5. The application thus relates also to solid oxide electrolyzer cells (SOEC).

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For the fuel cell mode as well as the reversed electrolyser mode, it is well known that protonic (H^+ ion) conduction can be use instead or oxygen ions conduction. Those are known under the terminology Proton exchange membrane fuel cells (PEMFC), The present invention can be applied to such protonic systems too, where the protonic membrane is obtained by a layer transfer technique from a host substrate, instead of for instance using an already formed polymer membrane.

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Membranes of solid oxide electrolyte can also be used for gas separation, like oxygen gas separation or hydrogen gas separation. In these cases, it may be necessary that the electrolyte not only allows for ionic conduction through the membrane but also for opposite charge carrier conduction like electrons or holes. Choice of the materials for the membrane depends on the targeted gas species. In the case of oxygen for instance perovskites are frequently used, like $Sr_{0.8}La_{0.2}Fe_{0.2}Co_{0.8}O_{3-\delta}$, $SrCo_{0.8}Fe_{0.2}O_{3-\delta}$ or $Sr_{0.5}Ba_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$. As another example, perovskites can also be used in the case of hydrogen (protons), like $LaScO_3$ and more generally oxides in the form $ACe_{1-x-y}X_xY_yO_3$ where $A=Ba, Sr$; X and $Y= Y, Yb, Zr, Tm$. Other materials like $SrCeO_3$, $BaCeO_3$, $CaZrO_3$, $SrZrO_3$ can also be used. In these applications too, one of the main challenges is to increase in a controlled way the conductivity of the membrane, pushing towards thinner and more uniform and denser layers. Among the applications, such membranes can be found in Air Separation Units for pure oxygen gas extraction from ambient air, in natural gas refining where CO_2 is removed after hydrogen extraction, and in many others.

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Figure 6 schematically shows how a solid electrolyte can be used in a chemical sensor, like an oxygen sensor. In the automotive world, such oxygen sensors may serve for instance to accurately define the air/fuel ratio in order to optimize the control of motor combustion efficiency. They may be placed in the exhaust system or earlier in the chain before the combustion chamber. Based on the utilization of ion conducting materials, several different principles do exist as to the working mechanisms of such sensors. One of them is based on the Nernst effect where an electrical potential is created across the sensor when there is a Oxygen Pressure (pO_2) gradient.

As schematically shown in Figure 6 a layer of solid electrolyte 111 is separating both sides A and B of an electrochemical conversion sensor 610. On both sides of the layer of solid electrolyte 111 there are contact structures 603 provided, using for instance well-known techniques and materials suitable for this sort of application. In particular the air tightness of the layer of electrolyte 111 is important and might be tuned by the layer transfer technique of our present invention as said layer could be prepared in high quality on substrates else than made of the material of the contact structures 603. The latter however need certain porosity for gas in order to allow contact with the layer of solid electrolyte 111. A reference chamber of known oxygen content and pressure may be used on one side of the sensor. A second type of oxygen sensor does measure the variation of the conductivity of the ceramic as a function of the Oxygen pressure (pO_2). Whatever the principle upon which the sensor is based, its accuracy and its sensitivity are critically depending on the control of the properties and dimensions of the ion-conducting membrane, which makes of the invention a real advantage. On the same principles, other gas than oxygen may also be detected using gas sensors and ion conducting membranes.

Figure 7 schematically illustrates one advantageous embodiment, an advanced structured donor substrate, that is a donor structure 701 comprising multiple donor layer of solid electrolyte 110 assembled to the

main surface of a large scale donor substrate 700 with a size large enough to accommodate multiple donor layers of solid electrolyte 110. The dimensions and shapes of the respective layers and substrates depicted in Figure 7 are non-limitative and only chosen for ways of illustration. Such a donor structure, or structured donor substrate, 701 is advantageous for large scale applications as a series connection of multiple SOFC in a final SOFC module. A high density of donor layers of solid electrolyte 110 can be easily obtained, the providing of the donor layers of solid electrolyte 110 on the donor substrate 700 can thereby be obtained by one of the techniques explained with respect to the present invention, or by application of ceramic glue or other suitable adhesive materials as for instance polymer based materials. One multiple transfer of layers of solid electrolyte 111 from a single structured donor substrate 701 as shown in Figure 7 on a receiver substrate 203 of at least the same size offers the possibility to easily integrate SOFC fabrication in an industrially viable environment, with the possibility to process in parallel large areas of electrolyte membranes.

In most of the examples treated so far, YSZ, in particular monocrystalline YSZ, was chosen as the solid electrolyte material. Other solid electrolyte material may be considered depending on the application and on the species to be selectively transported through the electrolyte. In particular for electrochemical battery applications, Li-ion or or Na-ion conductivity may be exploited too. For the latter, NaS batteries usually use β -Alumina for the solid electrolyte material. An alternative to the realization of such material by deposition is to use layer transfer techniques described in the present invention, based on the hypothesis that monocrystalline or high quality polycrystalline donor material are also developed separately. The same holds for Li-ion batteries, with solid electrolyte materials like LiPON or Li_3PO_4 . Other famous electrolyte materials, of interest here, are $\text{Na}_3\text{Zr}_2\text{Si}_2\text{PO}_{12}$ (NaSiCON), Na_2CO_3 and AgI.

CLAIMS

1. Method of providing a layer of solid electrolyte (111), the method comprising:
- providing a host substrate (100) including a crystalline solid electrolyte layer,
- transferring said crystalline solid electrolyte layer from the host substrate (100) to a receiver substrate (203), wherein the layer transfer technique (S11) comprises a step of assembling (S2) the host substrate (100) to a receiver substrate (203), the solid electrolyte layer being between said substrates, and a step of thinning (S3) the host substrate (100);

characterized by

the step of thinning (S3) comprising a step of formation (S4) of a zone of weakness (320) in the host substrate so as to define a portion of the host substrate comprising the layer to be transferred and a step of detaching (S5) at the zone of weakness (320) so as to transfer said portion to the receiver substrate.

2. Method of providing a layer of solid electrolyte (111) according to one of the preceding claims wherein the layer of solid electrolyte (111) is a monocrystalline layer.

3. Method of providing a layer of solid electrolyte (111) according to one of the claims 1 to 2, characterized in that the host substrate (100) comprises either a bulk substrate (101) of crystalline solid electrolyte material or a donor layer of crystalline solid electrolyte (110) provided on a support substrate (102).

4. Method of providing a layer of solid electrolyte (111) according to claim 3 characterized in that the donor layer of solid electrolyte (110) is provided on the support substrate (102) by a deposition technique, in particular chemical vapor deposition.

5. Method of providing a layer of solid electrolyte (111) according to claim 1 or according to claim 3 or 4 in combination with claim 1, wherein the step of formation (S4) of a zone of weakness (320) is obtained by implantation of atomic and/or ionic species.

6. Method of providing a layer of solid electrolyte (111) according to claim 1 or according to claim 3 or 4 in combination with claim 1, wherein the zone of weakness

(320) comprises a release layer (330) in the host substrate (100), said release layer being activated during the step of detaching (S5) in a way that detaching occurs.

7. Method of providing a layer of solid electrolyte according to claims 5 to 6 wherein the detaching step (S5) is obtained by at least one of: annealing, application of thermal stress, application of mechanic stress, application of irradiative means, in particular a laser beam, and etching.

8. Method of providing a layer of solid electrolyte (111) according to one of the preceding claims wherein the solid electrolyte material has ionic conductivity, in particular for hydrogen, oxygen, lithium or sodium ions, above 0.01 S/cm.

9. Method of providing a layer of solid electrolyte (111) according to one of the preceding claims wherein the layer of solid electrolyte (111) has a thickness in the range of 10 nm up to 100 μm with a variation in thickness below 5%, more preferentially below 1%.

10. Method of providing a layer of solid electrolyte (111) according to one of the preceding claims wherein the layer of solid electrolyte (111) has a defect density below a predetermined level, in particular lower than $5/\text{cm}^2$.

11. Method of providing a layer of solid electrolyte (111) according to one of the preceding claims wherein the material of the solid electrolyte layer (111) is a perovskite material and/or is chosen among the group of zirconia, ceria, gallates, alumina.

12. Method of providing a layer of solid electrolyte (11) according to one of the preceding claims wherein after transfer of the solid electrolyte layer onto the receiver substrate, there remains a portion of the host substrate which is further useable as host substrate for a subsequent transfer of a solid electrolyte layer.

13. Method of fabrication of a solid oxide fuel cell comprising an anode, a cathode, a layer of solid electrolyte in between said anode and cathode, and electrodes on the side of the anode and the cathode opposing to the layer of solid electrolyte, comprising carrying out the method according to one of claims 1 to 12 for transferring a crystalline solid electrolyte layer onto the anode and/or the cathode.

14. Method of fabrication of an oxygen sensor comprising two electrodes and a layer of solid electrolyte in between said two electrodes comprising carrying out the method

according to one of claims 1 to 12 for transferring a crystalline solid electrolyte layer onto the anode and/or the cathode.

15. Method of fabrication of a donor structure (701) comprising a donor substrate (700) having a main surface and a plurality of crystalline solid electrolyte layer portions on said main surface, wherein each of the plurality of crystalline electrolyte layer portions is obtained by the method according to one of claims 1 to 12.