DESCRIPTION

TITLE: METHOD FOR PRODUCING A FERROELECTRIC LAYER TRANSFERRED ONTO A SUBSTRATE AND HAVING IMPROVED POLARIZATION HOMOGENEITY

TECHNICAL FIELD OF THE INVENTION

[0001] The invention relates to a process for manufacturing a ferroelectric layer transferred onto a substrate and of improved polarization homogeneity in its thickness. Such a structure can be used to form, for example, radio frequency (RF) components, in particular elastic wave components, especially surface acoustic wave (SAW) or bulk acoustic wave (BAW) components.

TECHNOLOGICAL BACKGROUND

[0002] There are several types of applications that take advantage of, or are influenced by, the polarization properties of ferroelectric materials and the presence of domains with polarizations opposite to each other. These include electroacoustic devices such as Surface Acoustic Wave (SAW) devices and Bulk Acoustic Wave (BAW) devices. The existence of such applications has led to the development of methods for controlling the polarization domains of ferroelectric layers.

[0003] The article ""Seeing Is Believing"-In-Depth Analysis by Co-Imaging of Periodically-Poled X-Cut Lithium Niobate Thin Films", by Sven Reitzig et al., published in Crystals 2021, 11, 288, describes a lithium niobate layer integrated on a silicon substrate via a silica layer, and the control of the polarization of this layer parallel to the plane wherein it extends, by applying a voltage between electrodes arranged periodically on the free surface of the layer. It should be noted that, in such a structure with electrodes only on the free face of the crystal, controlling a polarization that would be perpendicular to the substrate by means

of an electric field, in the absence of a buried electrode, would require voltages that could cause the breakdown of the silica layer.

[0004] EP 0 592 226 A1 describes an optical frequency conversion device obtained by the periodic juxtaposition of parallel bands of inverted polarization on one face of a ferroelectric substrate exhibiting spontaneous polarization perpendicular to the plane of extension of the substrate, that is, perpendicular to this face. Reversing the polarization along the bands is achieved by proton exchange through a mask.

[0005] Document WO 2005/052682 A1 describes the localized polarization inversion of a ferroelectric crystal with spontaneous polarization perpendicular to one of its faces, by applying an electric field in juxtaposed periodic bands, using gel electrodes placed on that face and the opposite face of the crystal.

[0006] The structures and methods presented above, while they do enable the polarization domains of a ferroelectric layer to be controlled at its surface, remain impractical and do not allow polarization to be controlled through the thickness of this layer or its integration onto a support.

[0007] In response to these shortcomings, the international patent application with publication number WO 2020/200986 A1 and the French patent applications with filing numbers FR2301220 and FR2301221 propose techniques for transferring ferroelectric layers onto a substrate. However, these techniques do not solve the problem completely satisfactorily, in that, at the end of production, the transferred ferroelectric layers may exhibit uncontrolled polarization inhomogeneities in the layer thickness, particularly with regard to the transfer of ferroelectric layers with negative polarization onto the final support substrate.

DISCLOSURE OF THE INVENTION

[0008] One aim of the invention is to provide a method for manufacturing a ferroelectric layer transferred onto a substrate, the method correcting or preventing any polarization inhomogeneities that might appear in its thickness, in particular for the situation where a ferroelectric layer of negative polarization is sought, that is, oriented towards the support of the ferroelectric layer.

[0009] To achieve these aims, one aspect of the invention is a method for producing a composite structure comprising a ferroelectric layer with negative polarization resting on a support assembly, comprising the steps of providing a starting composite structure comprising a ferroelectric layer with positive polarization resting on the support assembly; and implanting hydrogen ions into the starting composite structure and then applying a heat treatment to the starting composite structure so as to reverse the polarization of the ferroelectric layer of the starting composite structure.

[0010] One advantage of the method according to the invention is its ability to produce a structure including a ferroelectric layer transferred onto a substrate and with a negative polarization, oriented towards the interface between the ferroelectric layer and its support, having an improved homogeneity over its thickness compared with known production methods. Such a structure facilitates the integration of bulk acoustic functions, for example, while keeping costs low and enabling a high level of performance.

[0011] According to additional non-limiting features of the invention, either individually or according to any technically feasible combination:

- the hydrogen ions can be implanted so that the initial composite structure has a hydrogen atom concentration of between 10^{19} and 10^{22} at/cm^3;
- the heat treatment applied can be set to bring the ferroelectric layer to a temperature between 300°C and the Curie temperature of this ferroelectric

layer, and preferably greater than or equal to 450°C, 500° or 550° and less than 600°C;

- the ferroelectric layer can extend in a horizontal direction and the positive polarization of the starting composite structure can be at an angle within an angular range of 20° to 160° to this horizontal direction;

- the ferroelectric layer can be a lithium niobate or lithium tantalate layer;

- the method may also comprise a step of polishing the ferroelectric layer;

- the method may further comprise obtaining the starting structure by a method which may comprise the steps of providing the support assembly; providing a donor substrate made of single-crystal ferroelectric material that has negative polarization with respect to a donor substrate face; forming an embrittlement plane in the donor substrate; joining the donor substrate to the support assembly by bringing the face into contact with the support assembly; and detaching a portion of the donor substrate at the embrittlement plane so as to leave the ferroelectric layer attached to the support assembly, thereby obtaining the starting structure;

- the method may further comprise obtaining the starting structure by a method comprising the steps of providing the support assembly; providing a donor substrate made of single-crystal ferroelectric material that has positive polarization with respect to a face of the donor substrate; forming an embrittlement plane in the donor substrate by implanting helium through the face; joining the donor substrate to the support assembly by bringing the face into contact with the support assembly; detaching a portion of the donor substrate at the embrittlement plane so as to leave the ferroelectric layer attached to the support assembly in order to obtain an intermediate structure; and applying a heat treatment to the intermediate structure so as to reverse the polarization of the ferroelectric layer and obtain the starting structure; and

- the heat treatment applied to the structure can be set to bring the ferroelectric layer to a temperature between 300°C and the Curie temperature of this ferroelectric layer, and preferably greater than or equal to 450°C, 500° or 550° and less than 600°C.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] Other features and advantages of the invention will emerge from the following detailed description of the invention with reference to the appended figures, wherein:

[Fig. 1] Figure 1 shows crystal cross-sections of single crystals;

[Fig. 2] Figure 2 shows the polarization reversal of a starting structure comprising a ferroelectric layer transferred onto a support, and having positive polarization;

[Fig. 3] Figure 3 is a diagram of a method for correcting the polarization of a ferroelectric material by means of ion implantation, as shown in Figure 2;

[Fig. 4] Figure 4 is a diagram of a first method for producing the starting structure of Figure 2;

[Fig. 5] Figure 5 shows the first manufacturing method;

[Fig. 6] Figure 6 shows the lack of influence of an implanted hydrogen concentration on the polarization of a ferroelectric layer;

[Fig. 7] Figure 7 is a diagram of a second method for producing the starting structure of Figure 2;

[Fig. 8] Figure 8 shows the second manufacturing method;

[Fig. 9] Figure 9 shows an angular range of polarizations.

DETAILED DESCRIPTION OF THE INVENTION

First embodiment of the invention

[0013] Depending on the piezoelectric device to be produced, an orientation must be chosen for the polarization of the active layer of piezoelectric material, which consists of a layer of single-crystal ferroelectric material.

[0014] This ferroelectric material can be obtained by crystal growth using the so-called "Czochralski" method, which produces a solid single-crystal material in an elongated cylindrical shape known as a "boule" or "ingot" by pulling a seed crystal of chosen orientation bathed in a molten material corresponding

to the crystal to be formed, in a pulling direction. The single crystal grows in this pulling direction. Wafers of the ferroelectric material are then obtained by cutting the ingot at a specific angle to its direction of growth, then prepared and integrated as a ferroelectric layer in, for example, a piezoelectric device.

[0015] The orientation of the layer polarization depends on the crystalline orientation of the cut wafer, which in the general case does not correspond to the direction of growth of the single crystal. Of course, the person skilled in the art will know how to select the most appropriate seed close to the desired crystalline orientation for pulling the ingot, in order to reduce material losses while it is being cut and machined into circular wafers.

[0016] Figure 1 shows, as (A) and (B), the orientations of $LiTaO_3$ layers designated 42RY and -138RY, respectively. These names derive from the crystallographic orientation of these layers, corresponding to respective rotations of 42° and -138° of the y and z axes with respect to the trigonometric direction around the x axis to give the x', y' and z' axes, the x, y and z axes corresponding to the single crystal's own crystallographic axes and the y' axis being aligned with the direction normal to the cut machined surface. More specifically, the x, y and z axes correspond to the axes $[\bar{1}\bar{1}20]$, $[01\bar{1}0]$, and $[0001]$, respectively.

[0017] After pulling in a chosen direction, it is known to the person skilled in the art to carry out polarization by applying an electric field in the z direction when the temperature falls below the Curie temperature, in order to determine the direction of polarization.

[0018] Conventionally, a negative polarization is a polarization with an orientation towards the interior of the material or structure in question; in other words, the projection of the z-axis onto the y'-axis is negative.

[0019] Conventionally, for a ferroelectric layer bonded to a substrate, a layer whose polarization orientation is towards the free surface of the layer is referred to as a positive-polarization layer.

[0020] Conversely, for a ferroelectric layer bonded to a substrate, a layer whose polarization orientation is inward, that is, towards the interface between the layer and its substrate, is referred to as a negative-polarization layer.

[0021] Figure 2 (A) shows a situation wherein the ferroelectric layer $Ferro_{lay}$ of $LiTaO_3$ RY42 has a positive polarization P_{42}: it is oriented towards the free surface, away from its substrate, or support assembly Sprt.Set, the latter here consisting of an interlayer Int on a support layer Sprt. It can also be said that the polarization component in the vertical direction Vert, which is perpendicular to the ferroelectric layer and oriented from the support assembly towards the ferroelectric layer, is positive. This component is obtained by normal projection of the polarization on the direction Vert.

[0022] To produce a piezoelectric device with a ferroelectric negatively-polarized layer, the characteristics of the ferroelectric wafer used to manufacture the device must be selected in advance, and the polarization orientation corrected if necessary.

[0023] Figure 2 shows the general principle of a manufacturing process for the structure EndStruct shown in (B), obtained by reversing the polarization of the structure StartStruct shown in (A).

[0024] The characteristics of the support assembly can affect the acoustic properties of the layer $Ferro_{lay}$, which is important in the case of a structure that forms part of an acoustic device. The nature and thickness of these layers can therefore also be decisive for carrying out the desired processing of an electrical signal, or at least influencing this processing. In the example shown in Figure 2, the support assembly may comprise the support layer Sprt, and

the intermediate dielectric assembly layer Int, preferably comprising an oxide directly in contact with the ferroelectric thin film $Ferro_{lay}$.

[0025] For reasons of availability and cost, the support layer Sprt can be made of silicon. This may be a support consisting of a solid base substrate of monocrystalline silicon, but the invention is not limited to this support, which may, more generally, be made of any material, for example silicon, even electrically insulating material such as sapphire or glass. The support layer Sprt, when formed from a solid substrate, is typically several hundred microns thick. One can limit the density of electrical charges, holes or electrons, which are likely to move in the support layer and could affect the proper operation of an RF component formed on the basis of the structure Struct. The support layer Sprt can thus be formed of a high-resistivity silicon substrate, that is, one having resistivity greater than 1000 ohm-centimeter, and more preferably still greater than 3000 ohm-centimeter. To reinforce the resistive nature of the support layer Sprt, the support layer Sprt can be provided with a charge-trapping layer on the ferroelectric layer side, for example one made of polycrystalline silicon. Of course, it is possible for this charge-trapping layer to be formed using a technique other than that of providing a layer made up of polycrystalline silicon. This layer may also comprise carbon or be made up of or comprise silicon carbide or an alloy of silicon and carbon. Alternatively, it may be a matter of producing the electrical traps by ion bombardment of relatively heavy species (for example argon) in a surface part of the support layer in order to create crystal defects therein that are capable of trapping electric charges. It is also possible to provide a charge-trapping layer made up of a porous material, for example by porosification of a surface part of the support layer Sprt when the latter is made of silicon. But the invention is not limited to a support layer with such characteristics.

[0026] By way of example, the intermediate layer Int may be made of silicon oxide or silicon nitride, or be formed of a stack of layers composed of these materials.

[0027] Alternatively, the intermediate layer can be an electrically conductive metal layer interposed between the ferroelectric layer $Ferro_{lay}$ and the support layer Sprt. In this example, the metal layer Int is in direct contact with both the support layer Sprt and the ferroelectric layer $Ferro_{lay}$. The layer Int can then be used as a buried electrode to apply an electric field to the ferroelectric layer $Ferro_{lay}$.

[0028] The presence of an intermediate layer Int is just one option. Not all applications require such a layer.

[0029] Conventionally, the structures StartStruct and EndStruct may take the form of a circular wafer with a diameter of 100, 200, 300 or even 450 mm, but the invention is by no means limited to this size or shape.

[0030] The ferroelectric layer $Ferro_{lay}$ may consist of a single-crystal ferroelectric material, such as lithium tantalate $LiTaO_3$ or lithium niobate LiNbO3, or materials such as $BaTiO_3$, $PbZrTiO_3$, $KNbO_3$, $BaZrO_3$, $PbTiO_3$ or $KTaO_3$ These materials also exhibit piezoelectric properties. Generally speaking, the ferroelectric layer can have a thickness of between 10 nanometers and 10 microns, depending on the intended application of the structure EndStruct and the expected component performance, but the invention does not rule out the use of different thicknesses, again depending on the intended application. It is noted that a ferroelectric material is a material that has electric polarization in the natural state, which polarization can be reversed by applying an external electric field greater than the coercive field of the material. As shown in the present document, the ferroelectric layer preferably has single-domain polarization, that is, all dipole moments are aligned parallel to each other in a given direction. Here, the given direction is inclined relative to the plane of the ferroelectric layer, that is, inclined relative to the free face of this layer.

[0031] With reference to Figures 2 and 3, the structure EndStruct shown in (B) can be obtained by reversing the polarization of the structure StartStruct

shown in (A) of Figure 2, according to a manufacturing method 100. The manufacturing method, summarized by the diagram in Figure 3, comprises steps S110, S120, S130 and S140, carried out in this order.

[0032] Step S110 is a step for providing a starting structure StartStruct consisting of a support layer Sprt, an intermediate layer Int and a ferroelectric layer $Ferro_{lay}$ as defined above. In this example, the layer $Ferro_{lay}$ is a $LiTaO_3$ RY42 layer with positive polarization P_{42}. More generally, the layer could be made of another ferroelectric material with a different polarization, as long as this polarization is positive.

[0033] Step S120 involves implanting H+ hydrogen ions into the structure StartStruct via the free face of the layer $Ferro_{lay}$. The implantation energy is chosen so that the projected path R_P of the implanted hydrogen ions is such that the depth $D(R_{PMax})$ of its maximum R_{PMax} reaches or exceeds the depth of the interface between the layer $Ferro_{lay}$ and the layer Int, and is preferably located in the layer Int, or in the layer $Ferro_{lay}$, or close to the layer Int. This situation is shown schematically in (A') of Figure 2, which shows the hydrogen concentration [H] as a function of the depth Dpth in the structure under consideration from the free surface of the layer $Ferro_{lay}$, in particular for a configuration in which the depth $D(R_{PMax})$ of the maximum R_{PMax} exceeds the depth of the interface between the layer Ferrolay and the layer Int. The distance between the depth of the interface and the depth $D(R_{PMax})$ can be chosen to be around 200 nm to avoid implanting too deep into the oxide. In another embodiment, this distance can reach or exceed 500 nm, so that the majority of ions and damage are located entirely within the layer Int, which can be advantageous. In yet another embodiment, the depth $D(R_{PMax})$ may be around 50 to 100 nm from the interface, but this time in the layer $Ferro_{lay}$, leaving the interface and also the layer Int intact and without implantation damage.

[0034] The resulting hydrogen ion distribution, with a gradient of hydrogen concentration, generates an electric field E_H directed towards the maximum

hydrogen concentration. A sufficient gradient can be achieved, for example, by means of hydrogen doping resulting in a hydrogen concentration exceeding a threshold of 10^{19} hydrogen atoms per cubic centimeter, for example with a hydrogen concentration of between 10^{19} and 10^{22} atoms/cm^3 at a plane parallel to the free surface of the layer $Ferro_{lay}$.

[0035] Step S130 is a heat treatment step for the structure, the heat treatment being designed to bring the ferroelectric layer to a temperature of between 300°C and the Curie temperature of the ferroelectric material of the layer $Ferro_{lay}$ (and preferably greater than or equal to 450°C, 500°C or 550°C, up to 600°C) for a period of between 30 minutes and 10 hours. This heat treatment is preferably carried out by exposing the free face of the dielectric layer to an oxidizing or neutral gaseous atmosphere.

[0036] The presence of the electric field E_H, combined with heat treatment at temperatures ranging from 300°C to 600°C, causes the polarization of the ferroelectric material to reverse as a result of the thermal activation triggered by the rise in temperature. More specifically, during heat treatment, the polarization of the ferroelectric material tends to take on the same orientation as the field E_H, thus reversing the polarization when E_H is oriented in a direction opposite to that of the material prior to heat treatment. This is precisely the case here, with positive polarization and an electric field E_H directed from the free surface of the layer $Ferro_{lay}$ towards its interface with the layer Int (in fact, towards the depth plane $D(R_{PMax})$, as shown in (A')).

[0037] In the case of a P_{42} polarization of the ferroelectric layer, reversing the polarization will result in the appearance of a polarization P_{-138}, opposite to the original polarization P_{42}.

[0038] Step S140 is a step of polishing the free face of the ferroelectric layer $Ferro_{lay}$, for example by mechanical, chemical-mechanical thinning techniques and/or chemical etching techniques. This polishing prepares the

free face so that (i) it has a low roughness, for example an RMS roughness of less than 0.5 nm over a 5 µm × 5 µm area, as measured by atomic force microscopy (AFM) and (ii) a surface layer of the layer $Ferro_{lay}$ is removed, which may exhibit inhomogeneous polarization and/or an oxide layer due to surface phenomena. For example, a removal thickness of 50 nm can be envisaged. This improves the homogeneity of the layer $Ferro_{lay}$ and its polarization.

[0039] As a result of step S140, the desired structure EndStruct is obtained, ready to be integrated into the manufacturing process of a complex component Dev such as a surface acoustic wave (SAW) or bulk acoustic wave (BAW) component.

Obtaining the starting structure StartStruct

[0040] Figures 4 to 8 show two alternative methods 1 and 2 for obtaining the starting structure StartStruct of the method 100.

Alternative method 1

[0041] Figures 4 to 6 show the alternative method 1 for obtaining the structure StartStruct, method 200 summarized by the diagram in Figure 4 and comprising the following steps.

[0042] A step S210 for preparing a support assembly Sprt.Set, here consisting of the support layer Sprt with the intermediate layer Int on its surface as shown in (A) of Figure 5.

[0043] A step S220 for selecting and supplying a wafer of single-crystal ferroelectric material for its chemical composition and crystalline orientation relative to its extension plane, for use as a ferroelectric donor substrate $Ferro_{sub}$. This wafer is where the layer $Ferro_{lay}$ will be formed. The chosen wafer has a single-domain negative polarization, that is, with a component

oriented opposite to the direction of its face designated by Top, that is, the wafer has a crystalline orientation between 0 RY and -180 RY, as shown by polarization P_{-138} in (B) of Figure 5. This is a polarization opposite in direction to that of the polarization of the desired structure StartStruct.

[0044] A step S240 for preparing the ferroelectric donor substrate $Ferro_{sub}$ to form an embrittlement plane Frgl for separating the ferroelectric layer $Ferro_{lay}$ from the donor substrate $Ferro_{sub}$ at a later stage, as shown in (B). The depth of the embrittlement plane Fgrl in the donor substrate $Ferro_{sub}$ defines the thickness of the ferroelectric layer $Ferro_{lay}$. How to obtain this plane will be explained below.

[0045] A step S250 for assembling the support assembly Sprt.Set with the donor substrate $Ferro_{sub}$, by bringing the free face Fr.Fac of the intermediate layer Int into contact with the Top face of the ferroelectric donor substrate $Ferro_{sub}$. The intermediate structure $Struct_{inter}$ thus formed is shown in (C), with the intermediate layer Int interposed between the support layer Sprt and the ferroelectric donor substrate $Ferro_{sub}$. The orientation of the ferroelectric donor substrate polarity with respect to the support layer is reversed, from P_{-138} to P_{42}, as a result of turning over the $Ferro_{sub}$ donor substrate for assembly.

[0046] Step S260 involves detaching part of the donor substrate $Ferro_{sub}$ from the intermediate structure $Struct_{inter}$ at the embrittlement plane, leaving the ferroelectric layer $Ferro_{lay}$ attached to the support Sprt and enabling the structure StartStruct to be obtained, as shown in (D). The ferroelectric layer $Ferro_{lay}$ has positive polarization P_{42} with respect to the normal Vert of the free surface used as a detachment interface.

[0047] Step S270 involves applying a stabilizing heat treatment to the structure StartStruct. The stabilizing heat treatment heals crystalline defects in the ferroelectric layer and helps consolidate the bond between this ferroelectric layer $Ferro_{lay}$ and the interlayer Int. In the case of $LiTaO_3$, this heat treatment is

designed to bring the ferroelectric layer to a temperature of between 300°C and the Curie temperature of the ferroelectric material (and preferably greater than or equal to 450°C, 500°C or 550°C, up to 600°C) for a period of between 30 minutes and 10 hours. This heat treatment is preferably carried out by exposing the free face of the dielectric layer to an oxidizing or neutral gaseous atmosphere.

[0048] It should be noted that in this case, the stabilization heat treatment will not reverse the polarization of the layer $Ferro_{lay}$. In fact, as shown by Figure 6, which shows the structure StartStruct after detachment, the hydrogen ions used to form the Frgl embrittlement layer exhibit a concentration gradient [H] whose maximum value is at the level of the embrittlement plane and which decreases continuously with distance from this plane, that is, from the free face of the layer $Ferro_{lay}$. The electric field generated by this concentration gradient is therefore directed towards the free surface of the layer $Ferro_{lay}$. So, even if a heat treatment is applied that could lead to polarization inversion, since both the existing polarization and the electric field are already oriented towards the free surface of the layer $Ferro_{lay}$, the polarization will remain unchanged. In this way, the structure PreStabStruct, which has not yet undergone the stabilizing heat treatment, can be considered to already be the initial structure StartStruct.

[0049] In a polishing step S280, a step of chemical-mechanical polishing, similar to step S140 of the method 100, is preferably applied to the free surface of the layer $Ferro_{lay}$, which has been roughened since the detachment step S260. However, given that the structure StartStruct is in any case intended to be polished in step S140 of the method 100, this step S280 remains optional.

[0050] Following steps S210 to S270 and, if necessary, step S280, the starting structure StartStruct of the method 100 is obtained.

[0051] The donor substrate $Ferro_{sub}$ shown in (B) is a substrate made from the ferroelectric material of the ferroelectric layer $Ferro_{lay}$. Alternatively, it could comprise a thin surface layer of this material. For example, the donor substrate

can be formed from a lithium tantalate or lithium niobate bulk substrate, or a composite substrate consisting of a first substrate on which a layer (at least equal to that of the layer $Ferro_{lay}$) of lithium tantalate or lithium niobate is applied. The use of a composite substrate comprising a support substrate and a layer of ferroelectric material is necessary if the difference in the coefficient of thermal expansion of the ferroelectric material and the final substrate is too great to enable the Smart Cut process to be applied. This approach is described in detail in documents WO2019002080 and WO2019186032, which are incorporated by reference herein.

[0052] The donor substrate thus comprises at least one layer of ferroelectric material having a first negative single-domain polarization P_{-138} inclined to the plane of extension of the ferroelectric layer $Ferro_{lay}$, which depends on the chosen crystalline orientation of the wafer. This layer is intended to be attached to the intermediate layer Int before being separated from the donor substrate.

[0053] Figure 5 shows a situation wherein the ferroelectric layer comes from a -138RY cut of $LiTaO_3$, with the orientation shown in (B) of Figure 1.

[0054] More generally, the method 200 applies to a crystalline cut in the range from 0RY to -180RY, preferably -20RY to -160RY, for the donor substrate $Ferro_{sub}$. The polarization of the resulting structure StartStruct is therefore positive, that is, oriented from 0° to 180°, preferably within an angular range [Ang] of 20° to 160°.

[0055] The ferroelectric layer $Ferro_{lay}$ can be transferred from the ferroelectric donor substrate $Ferro_{sub}$ using Smart Cut™ technology, in which case the donor substrate must be prepared by introducing light species such as hydrogen or helium into the donor substrate. This introduction may correspond to an implantation of hydrogen, that is to say, a bombardment of the planar face Imp of the donor substrate $Ferro_{sub}$ with hydrogen ions. In a manner known per se, and as shown in (B), the implanted hydrogen ions H^+ are

intended to form an embrittlement plane Frgl delimiting the ferroelectric layer $Ferro_{lay}$ of ferroelectric material to be transferred which is located on the side of the face Imp and another portion $Ferro_{sep}$ forming the remainder of the substrate and which will be separated from the ferroelectric layer $Ferro_{lay}$ at a later stage.

[0056] The nature, the dose of the implanted species, and the implantation energy are chosen as a function of the thickness of the film that is intended to be transferred and of the physico-chemical properties of the donor substrate $Ferro_{sub}$. In the case of a donor substrate made from $LiTaO_3$, it will thus be possible to choose to implant a hydrogen dose of between 10^{16} and 5×10^{17} at/cm² with energy that is between 30 and 300 keV to delimit a ferroelectric layer $Ferro_{lay}$ having a thickness of about 200 to 2000 nm.

[0057] In (C) of Figure 5, the polarization P_{42} is oriented away from the interface between the ferroelectric layer $Ferro_{lay}$ and the interlayer Int, so that the polarization of the ferroelectric layer is considered positive.

[0058] The support substrate Sprt may have the same size and shape as the donor substrate $Ferro_{sub}$, but the invention is not limited to such a configuration, and different sizes, shapes, and configurations may be employed. Prior to assembly, it is possible to envisage preparing the faces of the substrates to be assembled using a cleaning, brushing, drying, or polishing step, or using plasma activation.

[0059] This assembling may correspond to bringing the donor substrate $Ferro_{sub}$ into close contact with the support Sprt by molecular adhesion and/or electrostatic bonding, as mentioned for example in the French patent application published as no. 2 914 492.

[0060] As is well known, during a molecular adhesion method, the exposed surfaces of the support Sprt and the donor substrate $Ferro_{sub}$, which are

perfectly clean, flat and smooth, are brought into close contact to promote electrostatic bonding or the development of molecular bonds, for example of the van der Waals or covalent type. The two bodies are then assembled without the use of adhesives.

[0061] The assembly may comprise the application of low-temperature heat treatment (for example, between 50 and 300°C, typically 100°C) to sufficiently anneal out any crystalline defects present in the ferroelectric layer and increase the bonding energy to allow a final step of thinning, if any.

[0062] In the present embodiment, the step of detaching a portion of the donor substrate is performed by applying Smart Cut™ technology, according to which a layer intended to form the ferroelectric layer $Ferro_{lay}$ is delimited by the embrittlement plane Frgl defined by hydrogen ion implantation in the donor substrate, as shown in (B) of Figure 5. After the assembly step, this layer is detached from the donor substrate by fracture at the embrittlement plane and thus transferred to the support Sprt, as shown in (D) in Figure 5.

[0063] This detachment step may thus comprise applying to the intermediate structure $Struct_{inter}$ a heat treatment in a temperature range on the order of 80°C to 300°C to enable the detachment of the donor substrate portion from the ferroelectric layer $Ferro_{lay}$ and thus complete the transfer thereof to the support assembly. In place of or in addition to the heat treatment, this step may include the application of a blade or a jet of gaseous or liquid fluid, or any other force of a mechanical nature at the embrittlement plane Frgl.

Alternative method 2

[0064] Figures 7 and 8 show alternative method 2 for obtaining the structure StartStruct, which method 300 is summarized by the diagram in Figure 7.

[0065] Alternative method 2 is very similar to alternative method 1, with steps S310 to S380 substantially identical to steps S210 to S280, respectively, apart from the points detailed below.

[0066] In step S320, instead of choosing a negative-polarization donor substrate as in step S220, a positive-polarization donor substrate is chosen, P_{42} in Figure 8.

[0067] In step S340 of forming the embrittlement plane Frgl, instead of implanting hydrogen ions as in step S240, this time helium ions He^+ are implanted to form this plane.

[0068] The layer $Ferro_{lay}$ of the intermediate structure $Struct_{inter}$ obtained in step S350 has a negative polarization P_{-138}, opposite to the positive polarization P_{42} due to the donor substrate being turned over to be attached to the support assembly Sprt.Set. In this way, step S360, which separates part of the donor substrate Ferrosep to leave the layer Ferrolay on the support assembly, results in a PreStabStruct structure. This PreStabStruct structure is distinct from the desired structure StartStruct in that the polarization of the layer $Ferro_{lay}$ is of the opposite orientation to that desired, as shown in (D) of Figure 8.

[0069] However, as shown in (D') of Figure 8, the helium concentration [He] in the layer $Ferro_{lay}$ has a gradient with a maximum concentration at the free surface of the layer, as shown in Figure 8, which represents the structure PreStabStruct obtained just after separation, the helium ions used to form the embrittlement layer Frgl show a [He] concentration gradient with a maximum value on the embrittlement plane, decreasing continuously with distance from this plane, that is, from the free face of the layer $Ferro_{lay}$. The electric field generated by this concentration gradient is therefore directed towards the free surface of the layer $Ferro_{lay}$, opposite the polarization P_{-138}.

[0070] Thus, the application of a stabilizing heat treatment in step S370, according to parameters which may be those described in connection with step S130, results in a reversal of the polarization P_{-138} to give the polarization P_{42}, for the reasons explained above in connection with step S130. In fact, the concentration of helium implanted to form the embrittlement plane is sufficient to generate a polarization-reversing electric field E_{He} when heat treatment is applied. In this way, the structure PreStabStruct is modified to give the desired structure StartStruct. In other words, in alternative method 2, the heat treatment step S370 following the separation step is necessary to obtain the StartStruct structure, unlike the heat treatment step S270 in alternative method 1, where it is only optional and does not influence the polarization of the layer $Ferro_{lay}$.

[0071] Of course, a polishing step S380 similar to step S280 can be applied to smooth the free surface of the layer $Ferro_{lay}$.

[0072] As explained above, both of the alternative methods 1 and 2, the first one employing a negative-polarity donor substrate and a hydrogen implantation defining an embrittlement plane, and the second one employing a positive-polarity donor substrate and a helium implantation defining an embrittlement plane, enable the starting structure StartStruct of the method 100 to be obtained for a composite structure comprising a ferroelectric layer with negative polarity that is homogeneous in the thickness of the layer.

[0073] Although shown here for a crystalline-cut layer 42RY, the method 100 is more generally applicable to crystalline-cut layers in the range from 0RY to 180RY, preferably 20RY to 160RY, for the ferroelectric layer $Ferro_{lay}$ of the starting structure StartStruct. In other words, considering that the ferroelectric layer extends along a horizontal direction Hnz perpendicular to the vertical direction Vert normal to the layer, the positive polarization P_{42} of the starting structure StartStruct makes an angle within an angular range [Ang] ranging from 20° to 160° with respect to this horizontal direction Hnz, as shown in Figure 9. The polarization of the final structure EndStruct is negative, that is, oriented from 0° to

-180°, preferably within an angular range from -20° to -160°, relative to the plane of the ferroelectric layer $Ferro_{lay}$. Of course, the methods 200 and 300 can be adapted to select suitable crystalline cuts to obtain the structure StartStruct with the desired polarization of the ferroelectric layer $Ferro_{lay}$.

[0074] Figures in this document are not necessarily to scale. Some features and components may be shown exaggerated in relation to other components or in somewhat schematic form, and some details of conventional elements may not be shown in the interests of clarity and conciseness.

[0075] Naturally, the invention is not limited to the embodiments described, and it is possible to add alternative embodiments without departing from the scope of the invention as defined by the claims.

Claims

1. A method (100) of manufacturing a composite structure (EndStruct) comprising a ferroelectric layer ($Ferro_{lay}$) of negative polarization (P_{-138}) resting on a support assembly (Sprt.Set), comprising the steps of:

- providing (S110) a composite starting structure (StartStruct) comprising a ferroelectric layer ($Ferro_{lay}$) with positive polarization (P_{42}) resting on the support assembly (Sprt.Set); and

- implanting (S120) hydrogen ions (H+) into the starting composite structure (StartStruct) and then applying (S130) a heat treatment to the starting composite structure (StartStruct) so as to reverse the polarization (P_{42}) of the ferroelectric layer ($Ferro_{lay}$) of the starting composite structure (StartStruct).

2. The method (100) according to claim 1, wherein the hydrogen ions are implanted in such a way that the starting composite structure has a hydrogen atom concentration of between 10^{19} and 10^{22} at/cm^3.

3. The method according to claim 1 or 2, wherein the applied heat treatment (S130) is set to bring the ferroelectric layer ($Ferro_{lay}$) to a temperature between 300°C and the Curie temperature of this ferroelectric layer ($Ferro_{lay}$), and preferably greater than or equal to 450°C, 500°C or 550°C and less than 600°C.

4. The method (100) according to any of the preceding claims, wherein the ferroelectric layer extends in a horizontal direction (Hnz) and the positive polarization (P_{42}) of the starting composite structure (StartStruct) forms an angle within an angular range ([Ang]) of 20° to 160° with respect to this horizontal direction (Hnz).

5. The method (100) according to any of the preceding claims, wherein the ferroelectric layer ($Ferro_{lay}$) is a lithium niobate or lithium tantalate layer.

6. The method (100) according to any of the preceding claims, further comprising a step (S140) of polishing the ferroelectric layer ($Ferro_{lay}$).

7. The method (100) according to any of the preceding claims 1 to 6, further comprising obtaining the starting structure (StartStruct) by means of a method (200) comprising the steps of:

- providing (S210) the support assembly (Sprt.Set);

- providing (S220) a donor substrate (Ferrosub) of single-crystal ferroelectric material having a negative polarization (P_{-138}) with respect to a face (Top) of the donor substrate ($Ferro_{sub}$);

- forming (S240) an embrittlement plane in the donor substrate ($Ferro_{sub}$);

- assembling (S250) the donor substrate ($Ferro_{sub}$) to the support assembly (Sprt.Set) by bringing the face (Top) into contact with the support assembly (Sprt.Set); and

- detaching (S260) a portion of the donor substrate ($Ferro_{sub}$) at the embrittlement plane, so as to leave the ferroelectric layer ($Ferro_{lay}$) attached to the support assembly (Sprt.Set), thereby obtaining the starting structure (StartStruct).

8. The method (100) according to any of the preceding claims 1 to 6, further comprising obtaining the starting structure (StartStruct) by means of a method (300) comprising the steps of:

- providing (S310) the support assembly (Sprt.Set);

- providing (S320) a donor substrate ($Ferro_{sub}$) of single-crystal ferroelectric material having a positive polarization (P_{42}) with respect to a face (Top) of the donor substrate ($Ferro_{sub}$);

- forming (S340) an embrittlement plane in the donor substrate ($Ferro_{sub}$) by implanting helium (He^{+}) through the face (Top);

- assembling (S350) the donor substrate ($Ferro_{sub}$) to the support assembly (Sprt.Set) by bringing the face (Top) into contact with the support assembly (Sprt.Set);

- detaching (S360) a portion of the donor substrate ($Ferro_{sub}$) at the embrittlement plane, leaving the ferroelectric layer ($Ferro_{lay}$) attached to the support assembly (Sprt.Set) to obtain an intermediate structure (PreStabStruct); and

- applying (S370) a heat treatment to the intermediate structure (PreStabStruct) to reverse the polarization (P_{-138}) of the ferroelectric layer ($Ferro_{lay}$) and obtain the starting structure (StartStruct).

9. The method (100) according to claim 8, wherein the heat treatment (S370) applied to the structure (PreStabStruct) is set to bring the ferroelectric layer ($Ferro_{lay}$) to a temperature between 300°C and the Curie temperature of this ferroelectric layer ($Ferro_{lay}$), and preferably greater than or equal to 450°C, 500°C or 550°C and less than 600°C.