

## DESCRIPTION

**TITLE:** INTEGRATED STRUCTURE ATTACHED TO A SUBSTRATE,  
COMPRISING A FERROELECTRIC LAYER WITH SELECTIVE POLARISATION  
IN THE THICKNESS THEREOF, AND MANUFACTURING METHOD

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## TECHNICAL FIELD OF THE INVENTION

The invention relates to an integrated structure comprising  
a ferroelectric layer attached to a carrier, and to a method for  
10 manufacturing this structure. Such a structure can be used, for  
example, to form radiofrequency (RF) components, in particular  
bulk elastic wave components.

## TECHNOLOGICAL BACKGROUND

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Several types of application exist that leverage, or are  
influenced by, the polarisation properties of ferroelectric  
materials and the presence of polarisation domains that are  
opposite each other. These include surface acoustic wave (SAW)  
20 devices or bulk acoustic wave (BAW) devices. The existence of  
these applications has led to the development of methods for  
controlling the polarisation domains of the ferroelectric  
layers.

The article entitled, "Seeing Is Believing"-In-Depth  
25 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 by means of a silica layer,  
and controlling the polarisation of this layer parallel to the  
30 plane in which it extends, by applying a voltage between  
electrodes periodically disposed on the free surface of the  
layer. It should be noted that, in such a structure that only  
comprises electrodes on the sole free face of the crystal,  
controlling a polarisation that would be perpendicular to the  
35 substrate by means of an electric field, in the absence of an

embedded electrode, would require voltages that risk causing the silica layer to breakdown.

Document EP 0592226 A1 describes an optical frequency conversion device obtained by the periodic juxtaposition of parallel strips of inverted polarisation on a face of a ferroelectric substrate having a spontaneous polarisation perpendicular to the plane of extension of the substrate, i.e., perpendicular to this face. Polarisation inversion by strips is obtained by carrying out a proton exchange through a mask.

Document WO 2005/052682 A1 describes the localised inversion of the polarisation of a ferroelectric crystal with spontaneous polarisation perpendicular to one of its faces, by applying an electric field along juxtaposed periodic strips, by means of gel electrodes placed on this face and the face opposite the crystal.

The structures and methods described above, although they allow the polarisation domains of a ferroelectric layer to be effectively controlled on its surface, remain impractical and do not allow the polarisation to be controlled in the thickness of this layer and its integration on a carrier.

## **DISCLOSURE OF THE INVENTION**

A first aim of the invention is to provide a ferroelectric polarisation layer, optionally in a form that is integrated on a substrate, having polarisation domains with orientations that are opposite and perpendicular or oblique with respect to the plane of this layer, with the domains being distributed in the thickness of the ferroelectric layer, with said ferroelectric layer being able to be used with a view to applications based on bulk acoustic waves, for example. A second aim of the invention is a manufacturing method for obtaining the aforementioned integrated ferroelectric layer. A third aim of the invention is a method for the local and controlled inversion

of the polarisation of any ferroelectric element in the thickness thereof.

In order to achieve these objectives, a first aspect of the invention is a structure comprising a ferroelectric layer having a first polarization in a first volume and a second polarization, opposite the first polarization, in a second volume distinct from the first volume, wherein the first polarisation and the second polarisation are oriented perpendicularly or obliquely to the ferroelectric layer, a surface of the first volume forms a face of the ferroelectric layer and the first volume is interposed between this face of the ferroelectric layer and the second volume, the second volume has a higher hydrogen concentration, called polarity inversion concentration, than the first volume, and the polarity inversion concentration ranges between  $10^{19}$  and  $10^{22}$  hydrogen atoms per cubic centimetre.

An advantage of the structure according to the invention is the provision of an integrated structure, including a substrate, on which a ferroelectric layer is attached having a perpendicular or oblique polarisation with respect to the planes of extension of the layer and of the substrate, with this polarisation being modulated in the thickness of the ferroelectric layer. Such a structure facilitates, for example, the integration of bulk acoustic functions while keeping costs low.

According to additional non-limiting features of the first aspect of the invention, considered individually or according to any technically feasible combination:

- the structure can further comprise a carrier and a metal layer interposed between this carrier and the ferroelectric layer;
- the ferroelectric layer can be formed by a single-crystal;
- the ferroelectric layer can comprise lithium niobate or lithium tantalate;

- the carrier can comprise single-crystal silicon.

A second aspect of the invention relates to a method for manufacturing a structure with locally controlled polarisation, comprising the steps of providing a ferroelectric element having a first polarisation; enriching a given embedded volume of the ferroelectric element with hydrogen ions by ion implantation of the hydrogen ions through a face of the ferroelectric element, with a first volume of the ferroelectric element being interposed between the given embedded volume and the face of the ferroelectric element; and annealing the ferroelectric element after introducing the hydrogen ions, at a temperature ranging between 500°C and 700°C, so as to switch the first polarisation of the ferroelectric element in the given volume to a second polarisation with an opposite orientation to the first polarisation, with the first volume having the first polarisation after the annealing.

The method according to the invention is advantageous in that it is simple, flexible and can be easily integrated into a broader manufacturing method based on known and proven manufacturing techniques from the semiconductor industry. In addition, it allows the polarisation of a ferroelectric element to be controlled in the thickness thereof and is applicable to thin layers integrated on a substrate.

According to additional non-limiting features of the second aspect of the invention, considered individually or according to any technically feasible combination:

- the first polarisation can be mono-domain, perpendicular or oblique with respect to a face of the ferroelectric element;
- during the selective enrichment of the hydrogen ions, an implantation dose of hydrogen ions can be adapted so as to obtain a hydrogen concentration ranging between  $10^{19}$  and  $10^{22}$  hydrogen atoms per cubic centimetre;

- the hydrogen ion implantation can be implemented at an energy level ranging between 3 keV and 210 keV;
- the ferroelectric element can be a lithium niobate or lithium tantalate layer;
- 5 - the method can further comprise assembling a ferroelectric substrate and a carrier, followed by separating or thinning the ferroelectric substrate so as to define the ferroelectric element; and
- the carrier can be a single-crystal silicon substrate, and
- 10 a metal layer can be interposed between this single-crystal silicon substrate and the ferroelectric substrate.

#### **BRIEF DESCRIPTION OF THE FIGURES**

15 Further features and advantages of the invention will become apparent from the following detailed description of the invention, with reference to the appended figures, in which:

[Figure 1] Figure 1 shows a ferroelectric element with  
20 selectively modified polarisation in the thickness thereof and a corresponding manufacturing method according to the present description;

[Figure 2] Figure 2 shows alternative embodiments of the ferroelectric element of figure 1;

25 [Figure 3] Figure 3 illustrates a first method for integrating a ferroelectric layer on a carrier;

[Figure 4] Figure 4 illustrates a second method for integrating a ferroelectric layer on a carrier;

[Figure 5] Figure 5 is a schematic cross-sectional view of a  
30 device according to the present description;

[Figure 6] Figure 6 is a first variation of the device of figure 5; and

[Figure 7] Figure 7 is a second variation of the device of figure 5.

## DETAILED DESCRIPTION OF THE INVENTION

### Selective polarisation inversion by depth

5        Following a series of experiments, the applicant has realised that it is possible to switch the polarisation of polarisation domains by hydrogen implantation followed by annealing. These experimental results are implemented in the manufacturing method described hereafter, resulting in a  
10 ferroelectric element 10 having inverted polarisation domains at depths selected by the practitioner.

      The ferroelectric element 10 can be a ferroelectric single-crystal as such, this single-crystal can be in the form of a ferroelectric single-crystal layer, this ferroelectric crystal  
15 or this ferroelectric single-crystal layer can be attached to a carrier Sp<sub>prt</sub> within a structure Struct, such as the ferroelectric layer Ferro<sub>lay</sub> illustrated in section (D) of figure 3.

      Figures 1 and 2 illustrate a first embodiment, in which the ferroelectric element 10 is a ferroelectric single-crystal as  
20 such, i.e., independent of any carrier.

      Section (A) of figure 1 shows a cross-section, in a plane ZX, of the ferroelectric element 10 having two opposite faces Sup and Inf perpendicular to a direction Z and having a first single-domain polarisation P<sub>1</sub> parallel to the direction Z and  
25 perpendicular to the upper Sup and lower Inf faces, which are each parallel to the plane of extension of the ferroelectric element 10, i.e., the crystalline plane in which its dimensions are largest.

      For explanatory purposes, this embodiment uses the example  
30 of polarisation perpendicular to the plane of extension of the ferroelectric element 10. However, the invention also applies to the situation where the polarisation is not perpendicular to the plane of extension of the ferroelectric element 10 but is oblique thereto. The "perpendicular" feature refers to an incline of 90°

relative to the plane of extension of the ferroelectric element to the nearest 10°, the “oblique” or “obliquely” feature refers to an incline at least 5° away from the plane of extension of the ferroelectric element. A direction with an incline within  
 5 the range ranging from 5° to 80°, or from 30° to 70°, or even from 35° to 60° thus can be considered to be oblique. For example, a layer of LiTaO<sub>3</sub> 50RY and a layer of LiTaO<sub>3</sub> 42RY have polarisations inclined at 50° and 42°, respectively, relative to the plane of extension of the layer, and therefore have oblique  
 10 polarisations relative to the plane of extension of the layer.

In a step S10, the ferroelectric element 10 is enriched with hydrogen at a selective depth by selective ion implantation of hydrogen ions H<sup>+</sup> through the upper surface Sup, at an  
 15 implantation energy level ranging between 3 keV and 210 keV. The depth of the implantation and its extent in the direction Z are controlled by the implantation energy and the dose of implanted hydrogen ions.

As illustrated in section (B) of figure 1, this step S10 results in the formation of a relatively hydrogen rich volume V2  
 20 (indicated by the cross-hatching in the figures) in the ferroelectric element 10, directly below the upper surface Sup and on a relatively hydrogen poor volume V1 (white areas of the ferroelectric element 10), and with a depth depending on the acceleration energy of the implantation step. The volume V2 is  
 25 thus interposed between the non-implanted volume V1 and the upper surface Sup of the ferroelectric element 10. The implantation dose is adapted to the implantation energy so as to obtain a hydrogen density ranging between 10<sup>19</sup> and 10<sup>22</sup> atoms/cm<sup>3</sup> in the volume V2. It is possible to carry out several successive  
 30 implantations at different implantation energy levels and doses in order to better define the volume V2 and by homogenising the distribution of the hydrogen implanted in this volume.

At this stage, the polarisation of the entire ferroelectric element 10 remains unchanged in the implanted volumes, with the

implanted volume V2 and the regions of the non-implanted volume V1 still forming a single mono-domain in which the polarisation has only one orientation.

By way of an example, a dose of implanted hydrogen ions ranging between  $10^{14}$  and  $10^{15}$  at/cm<sup>2</sup> accelerated by a voltage of 6kV can be used to create a polarisation reversal volume V2 extending over approximately 50 nm in the thickness direction Z, in which volume V2 the hydrogen concentration ranges between  $10^{19}$  and  $10^{22}$ , preferably between  $5 \cdot 10^{19}$  and  $2 \cdot 10^{21}$  at/cm<sup>3</sup>. In all cases, the hydrogen-enriched volume V2 has a higher hydrogen concentration, called polarity inversion concentration, than the first volume V1.

In the present document, the YX and ZX planes are defined by the X, Y, Z axes of an orthogonal reference frame, with the YX plane being defined by the Y and X axes of the reference frame, the ZX plane being defined by the Z and X axes of the reference frame. The faces Sup and Inf of the ferroelectric element 10 extend parallel to the YX plane, perpendicular to the Z axis that defines the direction of extension of the thickness of the ferroelectric element 10. "Depth" is understood to mean a distance along the Z axis that is considered from the upper surface Sup. Furthermore, a modulation of the polarisation or of the hydrogen concentration of the ferroelectric element 10 in the thickness thereof is respectively understood to be variations in hydrogen concentration or changes in the direction of polarisation in the volume of this element in the direction Z.

In a step S20, the ferroelectric element 10 selectively enriched with hydrogen is annealed at a temperature ranging between 500°C and 800°C, preferably between 500°C and 700°C, more preferably between 550°C and 600°C. This annealing step causes an inversion of the first polarisation P1 of the ferroelectric element 10 only on the hydrogen-enriched volume V2 in order to yield a second polarisation P2, with the same

direction of alignment as the first polarisation P1, but in the opposite direction thereto, as illustrated in section (C<sub>0</sub>). Anti-parallel polarisations are defined as polarisations aligned in parallel directions but in opposite directions. Conversely, parallel polarisations are defined as polarisations aligned in parallel directions but in the same direction. Defining the volume V2 by hydrogen enrichment allows the polarisation inversion to be selective, propagating from the upper surface Sup throughout the volume V2 and thus transitioning from a parallel polarisation between the volumes V1 and V2 to an anti-parallel polarisation between the volumes V1 and V2. Annealing is preferably carried out in an oxygen atmosphere in order to reduce oxygen exodiffusion from the ferroelectric layer, but also can be carried out, for example, in a nitrogen or air atmosphere at atmospheric pressure for a duration ranging between 100 seconds and 10 hours.

The hydrogen concentration in the volume V2 obtained following step S10 is necessary for the polarisation inversion obtained in step S20, and for this reason can be referred to as the polarisation inversion concentration.

Sections (C1) and (C2) of figure 2 illustrate alternative embodiments for the volume V2, obtained by adjusting the number of implantations and their respective energy levels and doses. In section (C1), the implantation energy was sufficient to enrich part of the ferroelectric element 10 spaced apart from the surface Sup and reaching the lower surface Inf. The volume V2 therefore extends from the lower surface Inf of the ferroelectric element, while leaving a non-implanted volume V1 on the upper surface Sup side, so that a surface of the volume V1 forms a face (Sup) of the ferroelectric layer. In section (C2), hydrogen enrichment with a suitable concentration has affected the entire volume of the ferroelectric element 10, polarisation inversion is effective over the entire thickness of the crystal so that the volume V1 disappears, entirely replaced by the volume V2.

These alternative embodiments can be obtained by using hydrogen ion implantation sequences with suitable parameters.

As already mentioned, this first embodiment is illustrative and is not limited to controlling the polarisation of a single ferroelectric crystal, but can also be applied to more complex structures such as a ferroelectric crystal attached to a support, as will become apparent throughout the remainder of this disclosure.

#### Integration on a substrate - Solution 1

The method for selective polarisation inversion by depth in the ferroelectric layer described above is illustrated in figures 1 and 2 in the situation whereby it is applied to a single ferroelectric crystal, used as the ferroelectric element 10. This method for selective inversion by depth also can be applied to an assembly formed by a ferroelectric crystal integrated on a substrate, which assembly can then form the ferroelectric element 10 illustrated in figures 1 and 2.

The integration on a substrate can be carried out as explained hereafter with reference to figure 3, and with reference to publication WO 2020/200986 A1, which particularly describes attaching a thin single-domain ferroelectric layer to a substrate.

Figure 3 shows a method for manufacturing an integrated structure Struct illustrated in section (D), comprising a ferroelectric layer Ferro<sub>lay</sub> attached to a carrier Sprt with an electrically conductive metal layer M1 interposed between these two elements. In this example, the metal layer M1 is in direct contact with each one from among the carrier Sprt and the ferroelectric layer Ferro<sub>lay</sub>. The layer M1 subsequently can be used as an embedded electrode intended to apply an electric field to the ferroelectric layer Ferro<sub>lay</sub>. The presence of a metal layer M1 represents only one option and applications other than those of this example do not require the presence of such a layer.

Conventionally, the structure Struct can be in 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 these dimensions or to this shape.

5       The ferroelectric layer Ferro<sub>lay</sub> is made up of a single-crystal ferroelectric material, such as lithium tantalate LiTaO<sub>3</sub> or lithium niobate LiNbO<sub>3</sub>, or even of materials such as LiAlO<sub>3</sub>, BaTiO<sub>3</sub>, PbZrTiO<sub>3</sub>, KNbO<sub>3</sub>, BaZrO<sub>3</sub>, CaTiO<sub>3</sub>, PbTiO<sub>3</sub> or KTaO<sub>3</sub>. These materials also have piezoelectric properties. In general, the  
10 thickness of the ferroelectric layer can range between 10 nanometres and 10 microns, depending on the contemplated application of the structure Struct and the expected performance capabilities of the components, but the invention does not exclude the use of different thicknesses, still depending on the  
15 contemplated application. By way of a reminder, a ferroelectric material is a material that has electric polarisation in its natural state, which polarisation can be reversed by applying an external electric field that is greater than the coercive field of the material. As illustrated in the present document, the  
20 ferroelectric layer preferably has a first single-domain polarisation P<sub>1</sub>, i.e., all the dipole moments are aligned parallel to each other in a given direction. In this case, the given direction is the direction perpendicular to the plane of the ferroelectric layer, i.e., perpendicular to the free face of  
25 this layer, or even perpendicular to a surface plane of this layer.

For reasons of availability and cost, the carrier Sprt for its part is preferably selected from silicon. It can be a carrier made up of a solid single-crystal silicon base substrate, but  
30 the invention is not limited to this carrier, which can, more generally, be made up of any material, for example, silicon, even electrically insulating material such as sapphire or glass. When formed from a solid substrate, the thickness of the carrier Sprt is typically several hundred microns. In a single-crystal

silicon, the carrier Sp<sub>rt</sub> is electrically conductive, but preferably has high resistivity, greater than 1,000 ohms. This limits the density of any charges, holes or electrons, which are susceptible to move, which could affect the correct operation of an RF component formed on the basis of the structure Struct. However, the invention is not limited to a carrier with such features.

The thickness of the metal layer can range between a few nanometres and several microns, for example, 100 nm or more. It typically can be formed by a metal such as chrome, nickel, aluminium, platinum, titanium, tungsten, gold or by any combination of these elements with each other or with other metal elements, in a single layer or in a combination of layers.

With reference to figure 3, the structure Struct can be produced by a layer attachment manufacturing method comprising:

- preparing the carrier Sp<sub>rt</sub> illustrated in section (A), in this case forming the metal layer M1 on its surface;
- optionally preparing a ferroelectric donor substrate Ferro<sub>sub</sub> illustrated in section (B);
- assembling a first face of the carrier Sp<sub>rt</sub> and a face of the ferroelectric donor substrate Ferro<sub>sub</sub> in order to form an intermediate structure Struct<sub>inter</sub> illustrated in section (C) with the metal layer M1 interposed between the carrier Sp<sub>rt</sub> and the face of the donor of the ferroelectric substrate Ferro<sub>sub</sub>; and
- detaching part of the donor substrate Ferro<sub>sub</sub> from the intermediate structure in order to define the ferroelectric layer Ferro<sub>lay</sub> on the carrier Sp<sub>rt</sub> and to obtain the structure Struct illustrated in section (D).

The donor substrate Ferro<sub>sub</sub> illustrated in section (B) is a substrate made up of the ferroelectric material of the ferroelectric layer Ferro<sub>lay</sub>, or comprising a surface thickness of this material. Thus, by way of an example, the donor substrate can be formed by a solid substrate of lithium tantalate or

lithium niobate, or even by a composite substrate formed by a first substrate, on which a thickness (at least equal to that of the layer  $\text{Ferro}_{\text{lay}}$ ) of lithium tantalate or lithium niobate rests. The donor substrate preferably has a first single-domain polarisation  $P_1$  perpendicular to the implantation face  $\text{Imp}$  by which hydrogen ions  $\text{H}^+$  will be implanted in the donor substrate with a view to a subsequent detachment step. This orientation is conventionally achieved by selecting the growth mode of the crystal and its cutting plane.

The ferroelectric layer  $\text{Ferro}_{\text{lay}}$  can be transferred from the ferroelectric donor substrate  $\text{Ferro}_{\text{sub}}$  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 can correspond to hydrogen implantation, i.e., hydrogen ion bombardment of the flat face  $\text{Imp}$  of the donor substrate  $\text{Ferro}_{\text{sub}}$ . As is known per se, and as illustrated in section (B), the implanted hydrogen ions  $\text{H}^+$  are intended to form an embrittlement plane  $\text{Frgl}$  delimiting the ferroelectric layer  $\text{Ferro}_{\text{lay}}$  of ferroelectric material to be transferred that is located on the side of the face  $\text{Imp}$  and another part  $\text{Ferro}_{\text{sep}}$  forming the remainder of the substrate and that will be separated from the ferroelectric layer  $\text{Ferro}_{\text{lay}}$  in a subsequent step.

The type and dose of the implanted species and the implantation energy are selected as a function of the thickness of the layer to be transferred and of the physico-chemical properties of the donor substrate  $\text{Ferro}_{\text{sub}}$ . In the case of a donor substrate made of  $\text{LiTaO}_3$ , it is possible to choose to implant a dose of hydrogen ranging between  $10^{16}$  and  $5 \cdot 10^{17}$  at/cm<sup>2</sup> with an energy level ranging between 30 and 300 keV in order to delimit a ferroelectric layer  $\text{Ferro}_{\text{lay}}$  of the order of 200 to 2,000 nm thick.

Following the preparation of the carrier  $\text{Sprt}$  and of the donor substrate  $\text{Ferro}_{\text{sub}}$ , including the formation of the metal

layer M1 on the carrier or the donor substrate, these two elements are assembled by bringing them into contact, so that the metal layer M1 is interposed between the carrier Sprt and the ferroelectric layer Ferro<sub>lay</sub>, with said ferroelectric layer facing the carrier Sprt, so as to obtain the intermediate structure Struct<sub>inter</sub> illustrated in section (C) of figure 4. The carrier substrate Sprt can have the same size and shape as the donor substrate Ferro<sub>sub</sub>, but the invention is not limited to such a configuration and different sizes, shapes and configurations can be employed.

Prior to assembly, it is possible to contemplate preparing the faces of the substrates to be assembled by means of a step of cleaning, brushing, drying, polishing or plasma activation.

Assembly can involve bringing the donor substrate Ferro<sub>sub</sub> into close contact with the carrier Sprt by molecular adhesion and/or electrostatic bonding, as mentioned, for example, in the French patent application published under number 2914492.

As is well known, during a molecular adhesion method, the exposed surfaces of the carrier Sprt and of the donor substrate Ferro<sub>sub</sub>, which are perfectly clean, flat and smooth, are brought into close contact in order to promote electrostatic bonding or the development of molecular bonds, for example, of the Van der Waals or covalent type. The assembly of the two bodies is then achieved without using an adhesive.

Assembly can include applying a low temperature heat treatment (for example, ranging between 50 and 300°C, typically 100°C) so as to rectify any crystalline defects present in the ferroelectric layer and to sufficiently increase the bonding energy in order to allow an optional subsequent thinning step.

In the present embodiment, the step of detaching part of the donor substrate is carried out by applying Smart Cut™ technology, according to which a layer intended to form the ferroelectric layer Ferro<sub>lay</sub> is delimited by the embrittlement plane Fr<sub>gl</sub>. After the assembly step, this layer is detached from

the donor substrate by fracturing in the vicinity of the embrittlement plane  $Frgl$  and is thus attached to the carrier  $Sprt$ .

This detachment step can thus include applying a heat  
 5 treatment to the intermediate structure  $Struct_{inter}$  in a temperature range of the order of  $80^{\circ}C$  to  $300^{\circ}C$  in order to detach the part of the donor substrate from the ferroelectric layer  $Ferrol_{ay}$  and transfer it to the carrier substrate  $Sprt$ . As an alternative to or in addition to the heat treatment, this  
 10 step can include applying a blade or a jet of gaseous or liquid fluid, or any other mechanical force, to the embrittlement plane  $Frgl$ .

As an alternative to implementing the Smart Cut™ method described above, the step of detaching part of the donor  
 15 substrate can be replaced by a step of chemical-mechanical thinning of this ferroelectric donor substrate  $Ferro_{sub}$ .

Whether the removal of part of the thickness of the donor substrate is carried out by thinning or by fracturing, any type of finishing treatment can be applied to the structure  $Struct$   
 20 thus formed in order to allow the ferroelectric layer  $Ferrol_{ay}$  to comply with specifications in terms of thickness, thickness uniformity, roughness, crystalline quality or any other type of specifications.

In particular, with a view to using a ferroelectric layer  
 25  $Ferrol_{ay}$  that would have single-domain polarisation, a particular treatment can be applied to the ferroelectric layer  $Ferrol_{ay}$  attached to the substrate  $Subst$ , all with the aim of obtaining a single-domain polarisation of the ferroelectric layer  $Ferrol_{ay}$ .

For example, a preparation heat treatment can be applied to  
 30 the ferroelectric layer  $Ferrol_{ay}$ , followed by a thinning step.

The preparation heat treatment allows any crystalline defects present in the ferroelectric layer to be rectified. Furthermore, it can also help to consolidate the bond between this ferroelectric layer  $Ferrol_{ay}$  and the carrier  $Sprt$ . It also

has the effect, if the temperature is high enough, of causing the diffusion of the hydrogen contained in the ferroelectric layer and the multi-domain transformation of a surface portion of this ferroelectric layer. The thickness of this surface portion can be of the order of 50 nm or less and can extend over the entire extent of the ferroelectric layer. On completion of the preparation heat treatment, the ferroelectric layer has a relatively constant hydrogen concentration throughout its thickness. In the case of LiTaO<sub>3</sub>, this preparation heat treatment is designed to bring the ferroelectric layer to a temperature ranging between 300°C and the Curie temperature of the ferroelectric material (and preferably greater than or equal to 450°C, 500° or 550° in order to promote the hydrogen diffusion) for a duration ranging between 30 minutes and 10 hours. This heat treatment is preferably carried out by exposing the free face of the dielectric layer to an oxidising or neutral gaseous atmosphere, i.e., without covering this face of the thin layer with a protective layer that could prevent the exodiffusion of the hydrogen.

Following the preparation heat treatment, the ferroelectric layer is thinned. This thinning can correspond to polishing the free face of the ferroelectric layer Ferro<sub>lay</sub>, for example, using mechanical, chemical-mechanical thinning and/or chemical etching techniques. This allows the free face to be prepared so that it exhibits limited roughness, for example, less than 0.5 nm RMS 5x5 µm by atomic force measurement (AFM) and allows the multi-domain surface portion of the ferroelectric layer Ferro<sub>lay</sub> to be removed. In general, a thickness of 50 to 300 nm is removed in order to achieve the target thickness of the ferroelectric layer Ferro<sub>lay</sub>, and in all cases the thickness is greater than that of the multi-domain surface portion. Thus, a single-domain thin layer is formed with the required surface finish, crystalline quality and polarisation qualities.

Following the operations described above, a selective polarisation inversion as illustrated in figures 1 and 2 applied to the structure Struct illustrated in section (D) of figure 3 allows the structure Struct illustrated in section (D) of figure 4 to be formed.

#### Integration on a carrier - Solution 2

Solution 1 illustrates a method for assembling a donor substrate Ferro<sub>sub</sub> preferably having a first single-domain polarisation P1 perpendicular to a flat face of the substrate. Subsequently, a selective polarisation inversion can be applied to the ferroelectric layer Ferro<sub>lay</sub> of the obtained structure Struct in order to achieve two vertical polarisations in opposite directions within this ferroelectric layer.

This section discloses an alternative solution 2 to solution 1 in that, instead of applying a selective polarisation inversion after assembly, a selective polarisation inversion is applied to a donor ferroelectric substrate prior to assembly, as illustrated in figure 4.

Thus, unless otherwise indicated, reference can be made to solution 1 for all the steps of the assembly method illustrated in figure 4, including the alternative of thinning the donor substrate Ferro<sub>sub</sub> rather than fracturing said substrate. However, in this solution 2, the donor substrate Ferro<sub>sub</sub> has two vertical polarisations P1 and P2 in opposite directions. Such a substrate can, for example, be obtained from a single-domain polarisation substrate by selective polarisation inversion by depth, as illustrated in figures 1 to 2, and from the associated manufacturing method.

This solution allows a ferroelectric layer Ferro<sub>lay</sub> to be obtained whose surface polarisation is controlled without having to use a high-energy implantation.

This solution is also used to determine which of the volumes V1 and V2 will be located on the surface of the ferroelectric

layer Ferro<sub>lay</sub> in the structure illustrated in section (D) of figure 4. Indeed, depending on the depth location of the embrittlement plane Frgl, it can be located either (1) in the volume V1, as illustrated in figure 4, or (2) in the volume V2 (location not illustrated). In the first case, it is the volume V1, and therefore the polarisation P1, that will be located on the free surface of the ferroelectric layer Ferro<sub>lay</sub>, with the volume V2 being embedded below the volume V1, as illustrated in figure 4. In the second case, it is the volume V2, and therefore the polarisation P2, that will be located on the free surface of the ferroelectric layer Ferro<sub>lay</sub>, with the volume V1 being embedded below the volume V2.

Alternatively, based on the structure illustrated in section (D) of figure 4, a chemical-mechanical polishing step applied to the ferroelectric layer Ferro<sub>lay</sub> allows said layer to be thinned, optionally until the volume V2 is exposed, so that its surface forms the free face of the ferroelectric layer Ferro<sub>lay</sub>.

#### 20      Alternative embodiments

The examples illustrated above in figures 3 and 4 explicitly include only one metal layer M1, located between the carrier Sprt and the ferroelectric layer Ferro<sub>lay</sub>. Optionally, the structure can comprise an additional metal layer or optional dielectric layers at the interface between the carrier Sprt and the ferroelectric layer Ferro<sub>lay</sub>.

Figure 5 illustrates a structure Struct comprising a second metal layer M2 located on the surface of the ferroelectric layer, with the ferroelectric layer Ferro<sub>lay</sub> being interposed between the two metal layers M1 and M2. This configuration can be used as part of a bulk acoustic wave device, with the metal layers M1 and M2 acting as electrodes for applying an electric field to the ferroelectric layer Ferro<sub>lay</sub>.

Figure 6 illustrates a structure Struct further comprising a first dielectric layer, such as an oxide layer Ox1, interposed between the substrate Sprt and the first metal layer M1. This can be, for example, the result of a method for manufacturing the structure Struct in which the metal layer M1 is formed on the ferroelectric layer Ferro<sub>lay</sub>, the dielectric layer Ox1 is formed on the carrier Sprt, and then the ferroelectric layer Ferro<sub>lay</sub> is assembled on the carrier Sprt by bringing the metal layer into close contact with the dielectric layer, using a method similar to that explained in relation to figure 3, in this case with oxide-metal contact.

Figure 7 illustrates a structure Struct similar to that of figure 6, further comprising a second dielectric layer, such as an oxide layer Ox2 interposed between the first metal layer M1 and the first dielectric layer Ox1. This can be, for example, the result of a method for manufacturing the structure Struct in which the metal layer M1 and the second dielectric layer Ox2 are successively formed, and in this order on the dielectric layer Ferro<sub>lay</sub>, the dielectric layer Ox1 is formed on the carrier Sprt, then the ferroelectric layer Ferro<sub>lay</sub> is assembled on the carrier Sprt by bringing the two dielectric layers Ox1 and Ox2 into close contact, using a method similar to that explained in relation to figure 3, in this case with dielectric-dielectric contact, and more specifically oxide-oxide contact in this example.

The two methods explained above in relation to figures 6 and 7 are only two examples, and other methods can be contemplated, resulting in the same results or other alternative embodiments of the structure Struct. A Bragg mirror thus can be formed adjacent to the ferroelectric layer Ferro<sub>lay</sub>, preferably between this layer and the carrier Sprt, for example, below the metal layer M1, by forming a stack of pairs of layers comprising a layer of SiO<sub>2</sub> and a layer of HfS<sub>2</sub> or a layer of SiO<sub>2</sub> and a layer of Mo or other structures and materials known for forming Bragg mirrors. The metal layer M2 can have the same composition

as the layer M1 or can have a different composition. The oxide layers O<sub>x1</sub> and O<sub>x2</sub> can be, for example, silicon oxide or silicon nitride oxide layers.

In addition, the carrier Sprt can be prepared by adding a dielectric layer that can be formed from a stack of different types of dielectric layers. The dielectric layer can be produced directly on the carrier Sprt using various techniques that are known in the prior art, such as thermal oxidation or nitridation treatments, chemical depositions using techniques known as LPCVD (Low Pressure Chemical Vapour Deposition), PECVD (Plasma Enhanced Chemical Vapour Deposition), or even PVD (Physical Vapour Deposition) or ALD (Atomic Layer Deposition).

Assembling the carrier with the ferroelectric layer can cause hydrogen to accumulate at the interface between them, forming a gradient of hydrogen concentration allowing the multi-domain transformation of a portion of the ferroelectric layer close to this interface, for example, during the heat treatment for separating the ferroelectric layer Ferro<sub>lay</sub> from the ferroelectric substrate Ferro<sub>sub</sub>.

It is possible to ensure that the metal layer and the optional dielectric layers adjacent to the ferroelectric layer Ferro<sub>lay</sub> have a lower hydrogen concentration than that present in the ferroelectric layer Ferro<sub>lay</sub>, so that any excess hydrogen in the ferroelectric layer can be absorbed into these adjacent layers during the diffusion caused by the heat treatment for separating the layer Ferro<sub>sep</sub>. This prevents hydrogen from accumulating at the assembly interface and avoids a multi-domain transformation in the portion of the ferroelectric layer close to this interface.

The hydrogen concentration in the metal layer and in the optional dielectric layers can be reduced, for example, by means of an annealing step aimed at heating these adjacent layers to a temperature higher than that of the preparation heat treatment for the attached ferroelectric layer Ferro<sub>lay</sub>, which will be

subsequently described in this description. This layer thus can be brought to an annealing temperature of 600°C, 700°C, or even 800°C or more. The average hydrogen concentration in the dielectric layer, after this exodiffusion step, thus can be less  
5 than  $5 \cdot 10^{20}$  at/cm<sup>3</sup>, or advantageously less than  $10^{18}$  at/cm<sup>3</sup>.

The examples illustrated in this description are limited to a continuous volume V2 forming a single layer of inverted polarisation in the thickness of the ferroelectric layer, but it is possible to produce a pair of such volumes V2 respectively  
10 extending from two opposite surfaces of a piezoelectric layer, with a volume V1 with non-inverted polarisation and therefore opposite that of the two volumes V2 being interposed between these two volumes V2. The two distinct volumes V2 can be formed by carrying out several successive implantations of hydrogen  
15 ions with different acceleration energy levels and therefore different implantation depths, so as to define two volumes V2, each open on a surface of the ferroelectric layer and with thicknesses that are a function of the associated implantation energy levels. In this way, alternating opposite polarisations  
20 can be obtained in the thickness direction of the ferroelectric layer.

#### Examples of applications

Each of the structures illustrated in figures 5, 6 and 7  
25 can form a bulk acoustic wave device or can be integrated into such a device forming a BAW bandpass filter, for example.

Digital simulations were used to determine that such a device would have reduced frequency sensitivity with respect to the thickness and improved power efficiency, with the energy  
30 density in the layer being distributed over the entire thickness of the ferroelectric layer.

In this document, the figures are not necessarily to scale. Some features and some components may be shown enlarged relative

to other components or in a somewhat schematic form, and some details of conventional elements may not be shown in the interest of clarity and conciseness.

Of course, the invention is not limited to the embodiments  
5 described, and alternative embodiments can be applied thereto without departing from the scope of the invention as defined by the claims.

**CLAIMS**

1. Structure (Struct) comprising a ferroelectric layer (Ferro<sub>lay</sub>) having a first polarization (P1) in a first volume (V1) and a second polarization (P2), opposite the first polarization, in a second volume (V2) distinct from the first volume, **characterized in that** the first polarisation and the second polarisation are oriented perpendicularly or obliquely to the ferroelectric layer, a surface of the first volume (V1) forms a face (Sup) of the ferroelectric layer (Ferro<sub>lay</sub>) and the first volume (V1) is interposed between this face of the ferroelectric layer and the second volume (V2),  
wherein the second volume (V2) has a higher hydrogen concentration, called polarity inversion concentration, than the first volume (V1), and  
wherein the polarity inversion concentration ranges between  $10^{19}$  and  $10^{22}$  hydrogen atoms per cubic centimetre.
2. Structure according to Claim 1, further comprising a carrier (Sprt) and a metal layer (M1) interposed between this carrier and the ferroelectric layer.
3. Structure according to any one of Claims 1 to 2, wherein the ferroelectric layer is formed by a single-crystal.
4. Structure according to any one of Claims 1 to 3, wherein the ferroelectric layer comprises lithium niobate or lithium tantalate.
5. Structure according to Claim 2, wherein the carrier comprises single-crystal silicon.
6. Method for manufacturing a ferroelectric element (10), comprising the steps of:

- providing a ferroelectric element (10, Ferro<sub>lay</sub>) having a first polarisation (P1);

- enriching a given embedded volume (V2) of the ferroelectric element with hydrogen ions (H<sup>+</sup>) by ion implantation of the hydrogen ions (H<sup>+</sup>) through a face (Sup) of the ferroelectric element, with a first volume (V1) of the ferroelectric element (10) being interposed between the given embedded volume (V2) and the face (Sup) of the ferroelectric element; and

- annealing the ferroelectric element after introducing the hydrogen ions, at a temperature ranging between 500°C and 700°C, so as to switch the first polarisation (P1) of the ferroelectric element in the given volume (V2) to a second polarisation (P2) with an opposite orientation to the first polarisation (P1), with the first volume (V1) having the first polarisation (P1) after the annealing.

7. Method according to Claim 6, wherein the first polarisation (P1) is mono-domain, perpendicular or oblique with respect to a face (Sup) of the ferroelectric element.

8. Method according to Claim 6 or 7, wherein, during the selective enrichment with hydrogen ions, an implantation dose of hydrogen ions (H<sup>+</sup>) is adapted so as to obtain a hydrogen concentration ranging between 10<sup>19</sup> and 10<sup>22</sup> hydrogen atoms per cubic centimetre in the given volume (V2).

9. Method according to any one of Claims 6 to 8, wherein the ion implantation of hydrogen ions is implemented at an energy level ranging between 3 keV and 210 keV.

10. Method according to any one of Claims 6 to 9, wherein the ferroelectric element (10, Ferro<sub>lay</sub>) is a lithium niobate or lithium tantalate layer.

11. Method according to any one of Claims 6 to 10, further comprising assembling a ferroelectric substrate (Ferro<sub>sub</sub>) and a carrier (Sprt), followed by separating or thinning the  
5 ferroelectric substrate so as to define the ferroelectric element (Ferro<sub>lay</sub>).

12. Method according to Claim 11, wherein the carrier (Sprt) is a single-crystal silicon substrate, and a metal layer (M1) is  
10 interposed between this single-crystal silicon substrate and the ferroelectric substrate (Ferro<sub>sub</sub>).