

DESCRIPTION

TITLE: INTEGRATED STRUCTURE COMPRISING A FERROELECTRIC LAYER
WITH SELECTIVE POLARISATION ATTACHED TO A SUBSTRATE, 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 by means of a
10 dielectric layer, and to a method for manufacturing this
structure. Such a structure can be used to form non-linear
optical components or radiofrequency (RF) components, in
particular surface elastic wave components.

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TECHNOLOGICAL BACKGROUND

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
20 opposite each other. These include non-linear optics with, for
example, devices, called frequency doublers, that allow an
electromagnetic wave to be generated with twice the frequency as
that sent to the input of the device, by means of a periodically
polarised ferroelectric crystal. Surface acoustic wave (SAW)
25 devices also can be cited. 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
Analysis by Co-Imaging of Periodically-Poled X-Cut Lithium
30 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
plane in which it extends, by applying a voltage between
35 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 substrate by means of an electric field, in the absence of an
5 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
10 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
15 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.

20 The structures and methods described above, although they effectively allow the polarisation domains of a ferroelectric layer to be controlled, remain impractical and do not allow effective and safe control of a polarisation perpendicular to a face of a ferroelectric crystal, and even less so that of a
25 ferroelectric layer integrated on a carrier.

DISCLOSURE OF THE INVENTION

A first aim of the invention is to provide a ferroelectric
30 layer in a form that is integrated on a substrate, with polarisation having polarisation domains with orientations that are opposite and perpendicular or oblique with respect to the plane of this layer and are able to be used with a view to applications based on non-linear optics or 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
5 ferroelectric element.

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 zone and a second polarization, opposite the first polarization, in a second zone distinct from
10 the first zone, wherein the first polarisation and the second polarisation are oriented perpendicularly or obliquely to the ferroelectric layer, the second polarisation zone has a higher hydrogen concentration than the first polarisation zone, the structure further comprising a carrier and a dielectric layer
15 interposed between this carrier and the ferroelectric layer.

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 at least two distinct polarisations perpendicular or oblique with respect to
20 the planes of extension of the layer and of the substrate. Such a structure facilitates the integration of non-linear optical or surface acoustic functions, while keeping costs low.

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

- a hydrogen density in the second zone (V) can range between 10^{19} and 10^{22} atoms/cm³;
- the first zone and the second zone can define periodic patterns;
- 30 - the ferroelectric layer can be formed by a single-crystal;
- the ferroelectric layer can comprise lithium niobate or lithium tantalate;
- the dielectric layer can comprise silicon oxide;
- the carrier can comprise single-crystal silicon.

A second aspect of the invention relates to a method for manufacturing a structure for which the polarisation is locally controlled, comprising the steps of providing a ferroelectric element having a first polarisation; selectively enriching the ferroelectric element with hydrogen ions through a face of the ferroelectric element; and annealing the ferroelectric element after introducing the hydrogen ions, at a temperature ranging between 400°C and 700°C, so as to switch the polarisation of the ferroelectric layer in a volume defined by the selective introduction of the hydrogen ions.

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 local control of the polarisation of a ferroelectric element for which a single face is accessible and is therefore 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 polarisation can be mono-domain, perpendicular or oblique with respect to a face of the ferroelectric element;
- the selective enrichment of the hydrogen ions can be implemented by ion implantation of the hydrogen ions through a mask defining a region of the ferroelectric element not receiving hydrogen ions;
- the hydrogen ion implantation is at an energy level ranging between 3 keV and 210 keV;
- the selective introduction of the hydrogen ions can be provided by elements intended to form part of a surface acoustic wave device;

- the ferroelectric element can be a lithium niobate or lithium tantalate layer;
- 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;
- the carrier can be a single-crystal silicon substrate, and a dielectric layer comprising silicon oxide is interposed between this single-crystal silicon substrate and the ferroelectric substrate; and
- a dose of the selective enrichment of the ferroelectric element with hydrogen ions (H^+) can be adapted so as to obtain a hydrogen density ranging between 10^{19} and 10^{22} atoms/cm³ in said volume (V).

BRIEF DESCRIPTION OF THE FIGURES

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 selectively modified polarisation and a corresponding manufacturing method according to the present description;

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

[Figure 3] Figure 3 shows an alternative embodiment of the ferroelectric element of figure 1;

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

[Figure 5] Figure 5 illustrates a second method for integrating a ferroelectric layer on a carrier;

[Figure 6] Figure 6 is a schematic plan view of a device according to the present description;

[Figure 7] Figure 7 is a schematic cross-sectional view of the device of figure 6.

DETAILED DESCRIPTION OF THE INVENTION

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Selective polarisation inversion

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
 10 annealing. These experimental results are implemented in the manufacturing method described hereafter, resulting in a ferroelectric element 10 having polarisation domains with geometries selected by the practitioner.

The ferroelectric element 10 can be a ferroelectric single-
 15 crystal as such, this single-crystal can be in the form of a ferroelectric single-crystal layer, this ferroelectric crystal or this ferroelectric single-crystal layer can be attached to a carrier Sprt within a structure Struct, such as the ferroelectric layer Ferro_{lay} illustrated in section (D) of figure 4.

20 Figures 1 and 3 illustrate a first embodiment, in which the ferroelectric element 10 is a ferroelectric single-crystal as such, i.e., without being attached to a carrier.

Section (A) of figure 1 shows a cross-section, in a plane ZX, of the ferroelectric element 10 having two opposite faces
 25 Sup and Inf perpendicular to a direction Z and having a first single-domain polarisation P1 parallel to the direction Z and perpendicular to the upper Sup and lower Inf faces parallel to the plane of extension of the ferroelectric element 10, i.e., the crystalline plane in which its dimensions are largest.

30 For explanatory purposes, this embodiment uses the example of a 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 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 LiTaO₃ 50RY and a layer of LiTaO₃ 42RY have polarisations inclined at 50° and 42° , respectively, relative to the plane of extension of the layer, and therefore have oblique polarisations relative to the plane of extension of the layer.

In a step S10, the ferroelectric element 10 is selectively enriched with hydrogen by selective ion implantation of hydrogen ions H^+ , at an implantation energy level ranging between 3 keV and 210 keV. As illustrated in section (B) of figure 1, the selectivity of the implantation can be provided by forming a mask M using a conventional lithography method, which mask is made of resin, metal, oxide, nitride or any other material capable of stopping the hydrogen ions during implantation, so that the regions of the ferroelectric element covered by the mask do not receive hydrogen. For practical applications, the pattern formed by the mask M can be made up of a periodic pattern, for example, made up of strips of the same width that are parallel to each other and are constantly spaced apart, as illustrated in section (B_p) as a top view in the YX plane. Following implantation, the mask M is removed in this example.

This step results in the formation of relatively hydrogen-rich volumes V in the ferroelectric element 10, with a surface coverage corresponding to the negative of the pattern of the mask M and a depth depending on the acceleration energy of the implantation step. The volumes V thus form a periodic pattern in a direction within a plane parallel to the plane of extension of the ferroelectric element 10, i.e., in a direction within an outer surface of the ferroelectric element 10. The implantation

dose is adapted to the implantation energy so as to obtain a hydrogen density ranging between 10^{19} and 10^{22} atoms/cm³ in the volumes V. It is also possible to carry out several successive implantations at different implantation energy levels in order to better define the volumes V and by homogenising the distribution of the implanted hydrogen. At this stage, the polarisation of the entire ferroelectric element 10 remains unchanged in the implanted zones, with the implanted zones and the non-implanted zones still forming a single mono-domain in which the polarisation has only one orientation.

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 thickness of the ferroelectric element 10. In addition, selective implantation or selective enrichment is understood to mean implantation or enrichment in certain regions of the ferroelectric element 10, selected by the practitioner and in this case defined by the pattern of the mask M.

In a step S20, the ferroelectric element 10 selectively enriched with hydrogen is annealed at a temperature ranging between 400°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 volumes V 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, specific to the hydrogen-enriched volumes V as illustrated in section (C0). 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 and in the same direction. Inverting the polarisation only at the volumes V results in the transition from a configuration of parallel polarisations between the volumes V and the rest of the ferroelectric element 10 to a configuration of anti-parallel polarisations. 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 volumes V define a second zone having a second polarisation P2 different from, and in fact opposite to, a first polarisation P1 of a first zone defined by the volume of ferroelectric material included in the ferroelectric element 10 from which the second zone is removed. Thus, the first and second zones are complementary, with the sum of their parts forming the total volume of the ferroelectric material included in the ferroelectric element 10, i.e., the whole of a ferroelectric crystal when the ferroelectric element 10 is made up of such a crystal. The first zone and the second zone can be formed by disjunct volumes or can even form continuous volumes, depending on the shape given to the selective implantation region and its depth. During the manufacturing method, the second zone is enriched with hydrogen, so that the hydrogen concentration of the second zone is higher than the first zone.

Section (C0_P) of figure 1 illustrates the state of polarisation of the ferroelectric element 10 in the vicinity of the upper face Sup by means of a top view in the YX plane on completion of step S20, with domains with opposite polarisations with geometries defined by the volumes V obtained following the selective hydrogen enrichment by means of the mask M.

Sections (C1) and (C2) of figure 2 illustrate geometries for the volumes V obtained for increasing and higher implantation

energy levels than for the geometry illustrated in section (C0). In particular, in section (C2), the polarisation inversion is effective over the entire thickness of the crystal, which is achieved by a sufficiently high implantation energy level, depending on the distance between the faces Sup and Inf.

Figure 3 shows a sectional view (C3) and a plan view (C3_P) respectively corresponding to sections (C0) and (C0_P), illustrating an alternative embodiment in the method in step S10, in which the mask M is not removed following hydrogen implantation and step S20 is applied while the mask is still present. Polarisation inversion in the zones selectively enriched with hydrogen normally occurs in step S20. This alternative embodiment can be used, for example, in the event that it would be desirable to precisely align electrodes with reverse polarisation zones. In this case, the hydrogen-enriched zones are self-aligned with the electrodes used as masks for the selective hydrogen enrichment.

The selective polarisation inversion method described above is implemented by acting on only one face of the ferroelectric element. This feature therefore offers the possibility of controlling the polarisation of a ferroelectric element whose rear face is inaccessible or is too far from the front face, ensuring great flexibility in terms of the application of the method and its applicability to various geometries.

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, as will become apparent throughout the remainder of this disclosure.

Integration on a carrier - Solution 1

The method for selective polarisation inversion described above is illustrated in figures 1 to 3 in the situation whereby it is applied to a single ferroelectric crystal, used as the

ferroelectric element 10. This method for selective inversion 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 to 3.

5 The integration on a substrate can be carried out as explained hereafter with reference to figure 4, and with reference to publication WO 2020/200986 A1, which particularly describes attaching a thin single-domain ferroelectric layer to a substrate.

10 Figure 4 shows a method for manufacturing an integrated structure Struct illustrated in section (D), comprising a ferroelectric layer Ferro_{lay} attached to a carrier Sp_{rt} by means of a dielectric layer Diel. The layer Diel is in direct contact with each one from among the carrier Sp_{rt} and the ferroelectric
15 layer Ferro_{lay}.

Conventionally, the structure Struct can be in the form of a circular wafer, the diameter of which can be 100, 200, 300 or even 450 mm, but the invention is by no means limited to these dimensions or to this shape.

20 The ferroelectric layer Ferro_{lay} is made up of a single-crystal ferroelectric material, such as lithium tantalate LiTaO₃ or lithium niobate LiNbO₃, or even of materials such as LiAlO₃, BaTiO₃, PbZrTiO₃, KNbO₃, BaZrO₃, CaTiO₃, PbTiO₃ or KTaO₃. These materials also have piezoelectric properties. In general, the
25 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
30 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

ferroelectric layer preferably has a first single-domain polarisation P1, 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 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 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 Sprt 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 that would be formed on the basis of the structure Struct. However, the invention is not limited to a carrier with such features.

Optionally, the carrier Sprt can be provided with a charge trapping layer, which is a non-single-crystal layer having structural defects such as dislocations, grain boundaries, amorphous zones, interstices, inclusions, pores, etc. These structural defects form traps for the charges liable to flow through the material, for example, at the site of incomplete or pendant chemical bonds. Conduction is thus prevented in the trapping layer, which consequently has a high resistivity. Its thickness, notably when it is formed on a resistive carrier, can range between 0.1 and 3 μm . However, other thicknesses below or above this range are perfectly feasible, depending on the expected performance level of the structure. Advantageously, and

for reasons of simplicity of implementation, this trapping layer is formed by a layer of polycrystalline silicon. It can also include layers, or be formed entirely, of a silicon and carbon alloy. When present, this trapping layer is located on the side
 5 of the dielectric layer Diel. Other dielectric or electrically conductive layers with functionalities that are considered to be useful by the practitioner depending on the type of applications that are contemplated also can be present, adjacent to the dielectric layer Diel.

10 For its part, the thickness of the dielectric layer Diel can range between several nanometres and several microns, for example, 5 microns or more. It typically can be formed from an amorphous material, such as silicon oxide, silicon oxynitride or silicon nitride-silicon dioxide. It also can be an oxide such as
 15 Ta₂O₅, ZrO₂ or HfO or Al₂O₃.

With reference to figure 4, the structure Struct can be produced by a layer attachment manufacturing method comprising:

- preparing the carrier Sprt illustrated in section (A);
- optionally preparing a ferroelectric donor substrate Ferro_{sub}
 20 illustrated in section (B);
- assembling, via the dielectric layer Diel, a first face of the carrier Sprt and a face of the ferroelectric donor substrate Ferro_{sub} in order to form an intermediate structure Struct_{inter} as illustrated in section (C); and
- 25 - detaching part of the donor substrate Ferro_{sub} from the intermediate structure in order to define the ferroelectric layer Ferro_{lay} on the carrier Sprt and to obtain the structure Struct illustrated in section (D).

The carrier Sprt can be prepared by adding a dielectric
 30 layer Diel, as shown in section (A). This dielectric layer can be formed by a stack of different types of dielectric layers selected from the materials listed above, for example. The dielectric layer Diel 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
 5 ALD (Atomic Layer Deposition).

The donor substrate $\text{Ferro}_{\text{sub}}$ illustrated in section (B) is a substrate made up of the ferroelectric material of the ferroelectric layer $\text{Ferro}_{\text{lay}}$, or comprising a surface thickness of this material. Thus, by way of an example, the donor substrate
 10 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
 15 polarisation P_1 perpendicular to the implantation face Imp by which the hydrogen ions are implanted in the donor substrate. 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
 20 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 a flat
 25 face Imp of the donor substrate $\text{Ferro}_{\text{sub}}$. As is known per se, and as illustrated in section (B), the implanted hydrogen ions H^+ are intended to form an embrittlement plane Frgl delimiting the ferroelectric layer $\text{Ferro}_{\text{lay}}$ of ferroelectric material to be transferred that is located on the side of the face Imp and
 30 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 LiTaO_3 , it is possible to choose to implant a dose of hydrogen ranging between 10^{16} and $5 \cdot 10^{17}$ at/cm² 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 Sprt and of the donor substrate $\text{Ferro}_{\text{sub}}$, these two elements are assembled by bringing the free face of the dielectric layer into contact with the implantation face Imp of the donor substrate so as to obtain the intermediate structure $\text{Struct}_{\text{inter}}$ illustrated in section (C) of figure 4. The carrier substrate Sprt can have the same size and shape as those of the donor substrate $\text{Ferro}_{\text{sub}}$, but the invention is not limited to such a configuration and different sizes and shapes 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 $\text{Ferro}_{\text{sub}}$ into close contact with the carrier Sprt by molecular adhesion and/or electrostatic bonding. One function of the dielectric layer Diel formed on the carrier Sprt is to facilitate assembly. Alternatively, provision can be made for the dielectric layer Diel to be formed on the implantation face Imp of the donor substrate $\text{Ferro}_{\text{sub}}$, preferably before the formation of the embrittlement plane Frgl . It is also possible for the dielectric layer Diel to be formed in two parts, respectively on each one from among the carrier and the donor substrate.

As is well known per se, during a molecular adhesion method, the exposed surfaces of the carrier Sprt and of the donor substrate $\text{Ferro}_{\text{sub}}$ (with one and/or the other being covered with a dielectric layer intended to form the dielectric layer Diel), which are perfectly clean, flat and smooth, are brought into

close contact in order to promote 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.

5 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.

10 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 $\text{Ferro}_{\text{lay}}$ is delimited by the embrittlement plane Frgl . After the assembly step, this layer is detached from
15 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 treatment to the intermediate structure $\text{Struct}_{\text{inter}}$ in a
20 temperature range of the order of 80°C to 300°C in order to detach the part of the donor substrate from the ferroelectric layer $\text{Ferro}_{\text{lay}}$ and transfer it to the carrier substrate Sprt . As an alternative to or in addition to the heat treatment, this step can include applying a blade or a jet of gaseous or liquid
25 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 substrate can be replaced by a step of chemical-mechanical
30 thinning of this ferroelectric donor substrate $\text{Ferro}_{\text{sub}}$.

 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 thus formed in order to allow the ferroelectric layer $\text{Ferro}_{\text{lay}}$ 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 Ferro_{lay} that would have single-domain polarisation, the qualities of the dielectric layer Diel can be guaranteed and a particular treatment can be applied to the ferroelectric layer Ferro_{lay} attached to the substrate Subst, all with the aim of obtaining a single-domain polarisation of the ferroelectric layer Ferro_{lay}.

Indeed, assembly can cause hydrogen to accumulate at the interface between the dielectric layer and the ferroelectric layer, forming a gradient of hydrogen concentration allowing the multi-domain transformation of a portion of the ferroelectric layer in contact with the assembly layer during the heat treatment for separating the ferroelectric layer Ferro_{lay} from the ferroelectric substrate Ferro_{sub}.

With respect to the dielectric layer Diel, it is possible to ensure that it has a lower hydrogen concentration than that present in the ferroelectric layer Ferro_{lay}, so that any excess hydrogen in the ferroelectric layer can be absorbed into the dielectric layer during the diffusion caused by the heat treatment for separating the layer Ferro_{sep}. 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 dielectric layer Diel can be reduced, for example, by means of a step of annealing the dielectric layer Diel aimed at bringing this dielectric layer to a temperature higher than that of the preparation heat treatment for the attached ferroelectric layer Ferro_{lay}, 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 than $5 \cdot 10^{20}$ at/cm³, or advantageously less than 10^{18} at/cm³.

With respect to the ferroelectric layer Ferro_{lay}, a preparation heat treatment can be applied thereto, followed by
5 a thinning step.

The preparation heat treatment allows any crystalline defects present in the ferroelectric layer to be rectified. Furthermore, it helps to consolidate the bond between this ferroelectric layer Ferro_{lay} and the carrier Sp_{rt}. It also has
10 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
15 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 LiTaO₃, this preparation heat treatment is designed to bring the ferroelectric layer to a temperature
20 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
25 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
30 layer is thinned. This thinning can correspond to polishing the free face of the ferroelectric layer Ferro_{lay}, 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 $\text{Ferro}_{\text{lay}}$ to be removed. In general, a thickness of 100 to 300 nm is removed in order to achieve the target thickness of the ferroelectric layer $\text{Ferro}_{\text{lay}}$, and in all cases the thickness is greater than that of the multi-domain surface portion. Thus, a thin single-domain layer is formed with the required surface finish, crystalline quality and polarisation qualities.

A selective polarisation inversion as illustrated in figures 1 to 3 applied to the structure Struct illustrated in section (D) of figure 4 allows the structure Struct illustrated in section (D) of figure 5 to be formed.

Integration on a carrier - Solution 2

Solution 1 illustrates a method for assembling a donor substrate $\text{Ferro}_{\text{sub}}$ 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 $\text{Ferro}_{\text{lay}}$ 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 5.

Thus, unless otherwise indicated, reference can be made to solution 1 for all the steps of the assembly method illustrated in figure 5, including the alternative of thinning the donor substrate $\text{Ferro}_{\text{sub}}$ rather than fracturing said substrate. However, in this solution 2, the donor substrate $\text{Ferro}_{\text{sub}}$ has two vertical polarisations $P1$ and $P2$ in opposite directions. Such a substrate can be obtained, for example, from a single-domain polarisation substrate by selective polarisation inversion, as

illustrated in figures 1 to 3, and from the associated manufacturing method.

Example: surface acoustic wave device

5 By applying the selective polarisation inversion method illustrated in figures 1 to 3, so as to obtain a ferroelectric layer attached to a carrier and having two vertical polarisations P1 and P2 in opposite directions, as illustrated in section (D) of figure 5, it is possible, for example, to manufacture a
10 surface acoustic wave device Dev_{SAW} from a ferroelectric layer whose polarisation has been selectively modified.

Such a device, illustrated by the plan view of figure 7 and by figure 7 illustrating a cross-sectional view along the XX' axis of figure 6, conventionally comprises interdigitated
15 electrodes formed directly on the ferroelectric layer $\text{Ferro}_{\text{lay}}$. Using these electrodes El as a mask M, then indicated as M/El in figures 6 and 7, is advantageous during the selective introduction of hydrogen into the ferroelectric layer. Indeed, this method allows self-alignment of the inverted polarisation
20 volumes V with the interdigitated electrodes M/El. This yields the configuration indicated in section (C3) of figure 3. For the features and the method for manufacturing the elements of figures 6 and 7, please refer to the descriptions of said elements in figures 1 to 5.

25 It is worthwhile ensuring that the material for the electrodes is compatible with the annealing of step S20 intended to invert the first polarisation P1 of the ferroelectric layer $\text{Ferro}_{\text{lay}}$ in order to obtain a second polarisation P2 opposite the first polarisation P1 in the hydrogen-enriched volumes V.

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In this document, the figures are not necessarily to scale. Some features and 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 described, and alternative embodiments can be applied thereto
5 without departing from the scope of the invention as defined by the claims.

CLAIMS

1. Structure (Struct) comprising a ferroelectric layer (Ferro_{lay}) having a first polarization (P1) in a first zone and a second polarization (P2), opposite the first polarization, in a second zone (V) distinct from the first zone, **characterized in that** the first polarisation and the second polarisation are oriented perpendicularly or obliquely to the ferroelectric layer, the second polarisation zone (V) has a higher hydrogen concentration than the first polarisation zone, the structure further comprising a carrier (Sprt) and a dielectric layer (Diel) interposed between this carrier and the ferroelectric layer.
2. Structure according to Claim 1, wherein a hydrogen density in the second zone (V) ranges between 10^{19} and 10^{22} atoms/cm³.
3. Structure according to Claim 1 or 2, wherein the first zone and the second zone define periodic patterns.
4. Structure according to any one of Claims 1 to 3, wherein the ferroelectric layer is formed by a single-crystal.
5. Structure according to any one of Claims 1 to 4, wherein the ferroelectric layer comprises lithium niobate or lithium tantalate.
6. Structure according to any one of Claims 1 to 5, wherein the dielectric layer comprises silicon oxide.
7. Structure according to any one of Claims 1 to 6, wherein the carrier comprises single-crystal silicon.
8. Method for manufacturing a ferroelectric element (10), comprising the steps of:

- providing a ferroelectric element (10, Ferro_{lay}) having a first polarisation (P1);

- selectively enriching the ferroelectric element with hydrogen ions (H⁺) through a face (Sup) of the ferroelectric element; and

- annealing the ferroelectric element after introducing the hydrogen ions, at a temperature ranging between 400°C and 700°C, so as to switch the polarisation (P1) of the ferroelectric layer in a volume (V) defined by the selective introduction of the hydrogen ions.

9. Method according to Claim 8, wherein the polarisation (P1) is mono-domain, perpendicular or oblique with respect to a face (Sup) of the ferroelectric element.

10. Method according to Claim 8 or 9, wherein selective enrichment of the hydrogen ions is implemented by ion implantation of the hydrogen ions through a mask (M) defining a region of the ferroelectric element not receiving hydrogen ions.

11. Method according to any one of Claims 8 to 10, wherein the ion implantation of hydrogen ions is implemented at an energy level ranging between 3 keV and 210 keV.

12. Method according to any one of Claims 8 to 11, wherein the selective introduction of the hydrogen ions is provided by elements (M/El) intended to form part of a surface acoustic wave device.

13. Method according to any one of Claims 8 to 12, wherein the ferroelectric element (10, Ferro_{lay}) is a lithium niobate or lithium tantalate layer.

14. Method according to any one of Claims 8 to 13, further comprising assembling a ferroelectric substrate (Ferro_{sub}) and a carrier (Sprt), followed by separating or thinning the ferroelectric substrate so as to define the ferroelectric
5 element (Ferro_{lay}).

15. Method according to Claim 14, wherein the carrier (Sprt) is a single-crystal silicon substrate, and a dielectric layer (Diel) comprising silicon oxide is interposed between this
10 single-crystal silicon substrate and the ferroelectric substrate (Ferro_{sub}).

16. Method according to any one of Claims 8 to 15, wherein a dose of the selective enrichment of the ferroelectric element
15 with hydrogen ions (H⁺) is adapted so as to obtain a hydrogen density ranging between 10¹⁹ and 10²² atoms/cm³ in said volume (V).