

METHOD OF MANUFACTURING A MONOCRYSTALLINE LAYER, IN PARTICULAR A PIEZOELECTRIC LAYER

FIELD OF THE INVENTION

5 The present invention concerns a method of manufacturing a monocrystalline layer, in particular a piezoelectric layer, in particular for an application with a microelectronic, photonic or optical device. In particular, but non-restrictively, the said device may be a surface acoustic wave device, or a bulk acoustic wave device for radiofrequency applications.

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BACKGROUND TO THE INVENTION

Among the acoustic components used for filtering in the radiofrequency field, two main categories of filter can be distinguished:

15 - firstly, surface acoustic wave filters, known by the acronym SAW (Surface Acoustic Wave);

 - secondly, bulk acoustic wave filters and resonators, known by the acronym BAW (Bulk Acoustic Wave).

20 For a review of these technologies reference may be made to the article by W. Steichen and S. Ballandras, "Acoustic components used for filtering – Review of the different technologies", *Techniques de l'Ingénieur* [Engineering Technology], E2000, 2008 [1].

25 Surface acoustic wave filters typically include a thick piezoelectric layer (generally several hundred μm thick) and two electrodes in the form of interdigitated metal combs deposited on the surface of the said piezoelectric layer. An electrical signal, typically an electrical voltage variation, applied to an electrode, is converted into an elastic wave, which is propagated on the surface of the piezoelectric layer. Propagation of this elastic wave is facilitated if the frequency of the wave is equal to the frequency band of the filter. This wave is converted once more into an electrical signal when it reaches the other electrode.

30 For their part, bulk acoustic wave filters typically include a thin piezoelectric layer (i.e. generally roughly less than 1 μm thick) and two electrodes installed on each main face of the said thin layer. An electrical signal, typically an electrical voltage variation, applied to an electrode, is converted into an elastic wave, which is propagated through the piezoelectric layer. Propagation of this elastic wave is facilitated if the frequency of the wave is equal to the frequency band of the filter. This wave is converted once more into an electrical signal when it reaches the electrode on the opposite face.

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In the case of surface acoustic wave filters the piezoelectric layer must be of excellent crystalline quality in order not to cause any attenuation of the surface wave. In this case a monocrystalline layer will therefore be preferred. Currently, suitable materials which can be used industrially are quartz, LiNbO_3 or LiTaO_3 . The piezoelectric layer is
 5 obtained by cutting an ingot of one of the said materials, wherein the accuracy required for the thickness of the said layer is unimportant if the waves are to be propagated essentially on its surface.

In the case of bulk acoustic wave filters the piezoelectric layer must have a determined and uniform thickness throughout the entire layer, in a precisely controlled
 10 manner. Conversely, since crystalline quality is secondary in terms of the important criteria for performance of the filter, compromises are currently made concerning the crystalline quality of the said layer, and a polycrystalline layer has for a long time been considered to be acceptable. The piezoelectric layer is therefore formed by deposition on a supporting substrate (for example a silicon substrate). At the current time the materials
 15 used industrially for such deposition are AlN , ZnO and $\text{Pb}(\text{Zr}_x\text{Ti}_{1-x})\text{O}_3$ (PZT).

The choice of materials is therefore very limited with both technologies.

But the choice of a material is the outcome of a compromise between different properties of the filter, depending on the specifications of the filter manufacturer. In particular, the electromechanical coupling coefficient of piezoelectric materials are criteria
 20 for the choice of material which must be used for a given application and a given component architecture.

For example, LiNbO_3 and LiTaO_3 are highly anisotropic materials. Since the coupling coefficient depends on the crystalline orientation the choice of a particular orientation of the material provides a first degree of freedom for the choice of material. This is why
 25 substrates can be found with a multiplicity of crystalline orientations, for example: X-cut, Y-cut, Z-cut, YZ-cut, 36° rotated Y axis, 42° rotated Y axis, etc.

However, except for the fact that they are able to select a particular crystalline orientation, those skilled in the art have only quartz, LiNbO_3 and LiTaO_3 to design a surface acoustic wave filter, giving only a limited range of parameters to optimise the
 30 filter's characteristics, even if several other materials may in future be added to this list, such as langasite $\text{La}_3\text{Ga}_5\text{SiO}_{14}$, for example.

To allow more freedom in dimensioning bulk acoustic wave filters or surface acoustic wave filters, it would be desirable to be able to use more materials than the materials listed above, provided the quality of the materials is not impaired.

BRIEF DESCRIPTION OF THE INVENTION

One aim of the invention is to remedy the above-mentioned disadvantages, and in particular to devise a method of manufacturing a monocrystalline layer, in particular a piezoelectric layer, in particular for a surface acoustic wave device, made of materials other than the materials used for this application, in particular by enabling layers to be obtained which are thin (i.e. less than 20 μm thick, or less than 1 μm thick) and uniform, made of the materials used for surface acoustic wave devices. This method must also enable a larger variety of supporting substrates to be used than in existing bulk acoustic wave devices.

In accordance with the invention, a method of manufacturing a monocrystalline layer is proposed characterised by the fact that it includes the following successive steps:

- provision of a donor substrate comprising a piezoelectric material of composition ABO_3 , where

A consists of at least one element from among: Li, Na, K, H;

B consists of at least one element from among: Nb, Ta, Sb, V;

- provision of a receiver substrate,

- transfer of a layer called the "seed layer" from the donor substrate on to the receiver substrate, by bonding the donor substrate on the receiver substrate such that the seed layer is at the bonding interface, followed by thinning of the donor substrate as far as the said seed layer;

- growth, by epitaxy on piezoelectric material ABO_3 of the seed layer, of a monocrystalline layer of composition $\text{A}'\text{B}'\text{O}_3$, where:

A' consists of a least one of the following elements: Li, Na, K, H;

B' consists of a least one of the following elements: Nb, Ta, Sb, V;

A' is different from A or B' is different from B.

The expression "layer at the bonding interface" is understood to mean a layer on the side of the face of a first substrate which is bonded to a second substrate, but does not necessarily imply that there is direct contact between the said layer and the second substrate. The said layer can thus be bonded directly to the second substrate, or be covered by a bonding layer, for example a dielectric layer, or any other type of layer, through which the bonding is accomplished.

The expression "A is different from A'" is understood to mean that A and A' consist of different elements and/or of the same element(s), but in different stoichiometric proportions.

According to one implementation, A' includes at least one element in common with A, and/or B' includes at least one element in common with B.

The expression "A' includes at least one element in common with A" is understood to mean that a given element (or several elements) are present both in A and in A', in identical or different stoichiometric proportions.

According to one implementation, A' is identical to A when B' is different from B, and
 5 B' is identical to B when A' is different from A.

The expression "A' is identical to A" is understood to mean that A' and A consist of the same element(s), in the same stoichiometric proportions.

According to one implementation, A consists of a single element and B consists of a single element.

10 According to one way of executing the invention the transfer of the seed layer includes the following steps:

- formation of an embrittlement area in the donor substrate so as to delimit a layer, called the seed layer, containing the said piezoelectric material of composition ABO_3 ,
- bonding of the donor substrate on the receiver substrate, where the seed layer is
 15 at the bonding interface,
- detachment of the donor substrate along the embrittlement area so as to transfer the seed layer on to the receiver substrate.

Before the step of epitaxy a proportion of the thickness of the seed layer transferred on to the receiver substrate can be removed.

20 Advantageously the thickness of the seed layer is less than 2 μm , and preferably less than 1 μm .

The receiver substrate is advantageously made of a semiconductor material, and includes an intermediate charge-trapping layer between the seed layer and the receiver substrate.

25 Another object of the invention relates to a method of manufacturing a monocrystalline layer, characterised by the fact that it includes the following successive steps:

- provision of a donor substrate comprising a piezoelectric material of composition $A'B'O_3$, where
 30 A' consists of one or more of the following elements: Li, Na, K, H;
 B' consists of one or more of the following elements: Nb, Ta, Sb, V;
- growth by epitaxy on the said piezoelectric material $A'B'O_3$ of a monocrystalline layer of composition $A''B''O_3$, where
 35 A'' consists of one or more of the following elements: Li, Na, K, H;
 B'' consists of one or more of the following elements: Nb, Ta, Sb, V;
- supply of a receiver substrate,
- transfer of at least a proportion of the epitaxial layer of composition $A''B''O_3$ on to the receiver substrate by bonding of the donor substrate on the receiver substrate through

the said epitaxial layer, followed by thinning of the donor substrate as far as the said epitaxial layer of composition $A''B''O_3$.

According to one implementation, after layer of composition $A''B''O_3$ has been transferred on to the receiver substrate, a monocrystalline layer of composition $A'''B'''O_3$ is made to grow, by epitaxy, on the said material of composition $A''B''O_3$, where, in composition $A'''B'''O_3$,

A''' consists of one or more of the following elements: Li, Na, K, H;

B''' consists of one or more of the following elements: Nb, Ta, Sb, V.

According to one implementation, A''' is different from A'' or B''' is different from B'' .

According to one way of executing the invention, the transfer of the said at least proportion of the epitaxial layer of composition $A''B''O_3$ on to the receiver substrate includes the following steps:

- formation of an embrittlement area in the donor substrate or in the epitaxial layer of composition $A''B''O_3$, so as to delimit a layer which is to be transferred,
- bonding of the donor substrate on to the receiver substrate, where the epitaxial layer of composition $A''B''O_3$ is at the bonding interface;
- detachment of the donor substrate or of the epitaxial layer along the embrittlement area.

According to one implementation the embrittlement area is formed in the donor substrate and, after the transfer step, the transferred layer is thinned so as to expose the material of composition $A''B''O_3$.

According to one implementation, A'' is different from A' or B'' is different from B' .

According to one implementation, A'' includes at least one element in common with A' , and/or B'' includes at least one element in common with B' .

According to one implementation, A'' is identical to A' when B'' is different from B' , and B'' is identical to B' when A'' is different from A' .

According to one implementation, A' consists of a single element and B' consists of a single element.

According to one particular way of executing the invention, the embrittlement area is formed by ion implantation in the donor substrate.

In a particularly advantageous manner, after the step of epitaxy the thickness of monocrystalline layer of composition $A''B''O_3$ is between 0.2 and 20 μm .

In addition, at least one electrically insulating layer and/or at least one electrically conducting layer can be formed at the interface between the receiver substrate and the donor substrate.

According to one way of executing the invention, the said method includes the transfer of at least a proportion of the monocrystalline layer of the receiver substrate on to a final substrate.

Another object relates to a substrate for a microelectronic, photonic or optical device, characterised by the fact that it includes a support substrate and a monocrystalline layer of composition $A''B''O_3$ on the said support substrate, where

A'' consists of one or more of the following elements: Li, Na, K, H;

5 B'' consists of one or more of the following elements: Nb, Ta, Sb, V;

at least one of A'' and B'' consists of at least two elements,

and a layer of composition $A'B'O_3$, where

A' consists of at least one element from among: Li, Na, K, H, and

B' consists of at least one element from among: Nb, Ta, Sb, V,

10 between the support substrate and the layer of composition $A''B''O_3$.

According to one implementation the said substrate also includes, on the layer of composition $A''B''O_3$, a monocrystalline layer of composition $A'''B'''O_3$, where

A''' consists of one or more of the following elements: Li, Na, K, H;

B''' consists of one or more of the following elements: Nb, Ta, Sb, V.

15 Another object concerns a method of manufacturing a surface acoustic wave device including the deposition of electrodes on the surface of a monocrystalline piezoelectric layer, characterised by the fact that it includes the manufacture of the said piezoelectric layer by a method as described above.

Another object concerns a surface acoustic wave device characterised by the fact
20 that it includes a monocrystalline piezoelectric layer which can be obtained by a method as described above, and two electrodes installed on the surface of the said monocrystalline piezoelectric layer.

Another object concerns a method of manufacturing a bulk acoustic wave device including the deposition of electrodes on two opposite faces of a monocrystalline
25 piezoelectric layer, characterised by the fact that it includes the manufacture of the said piezoelectric layer by a method as described above.

Another object concerns a bulk acoustic wave device characterised by the fact that it includes a monocrystalline piezoelectric layer which can be obtained by a method as described above, and two electrodes installed on two opposite faces of the said
30 monocrystalline piezoelectric layer.

Another object of the invention concerns a micro-sensor designed to measure a deformation caused by an external stress, characterised by the fact that it includes a monocrystalline piezoelectric layer which can be obtained by a method described above

Another object of the invention concerns a micro-actuator designed to cause a
35 deformation of an element or motion of a moving part, through the application of a continuous or variable electric field, characterised by the fact that it includes a monocrystalline piezoelectric layer which can be obtained by a method described above.

BRIEF DESCRIPTION OF THE ILLUSTRATIONS

Other characteristics and advantages of the invention will be seen clearly from the detailed description given below, with reference to the appended illustrations, in which:

- figure 1 is a section functional view of a surface acoustic wave filter,
- 5 - figure 2 is a section functional view of a bulk acoustic wave filter,
- figures 3A to 3E illustrate successive steps of a method of manufacturing a monocrystalline layer according to a first implementation of the invention;
- figures 4A to 4E illustrate successive steps of a method of manufacturing a monocrystalline layer according to a second implementation of the invention;
- 10 - figure 4F illustrates an additional step implemented in a variant of the implementation illustrated in figures 4A to 4E;
- figures 5A to 5C illustrate optional subsequent steps of the said method.

For reasons of legibility of the figures the illustrated elements are not necessarily represented at scale. Elements designated by the same reference signs in different
15 figures are identical.

DETAILED DESCRIPTION OF IMPLEMENTATIONS OF THE INVENTION

Figure 1 is a functional view of a surface acoustic wave filter.

Said filter includes a piezoelectric layer 10 and two electrodes 12, 13, in the form of
20 two interdigitated metal combs deposited on the surface of said piezoelectric layer. On the side opposite electrodes 12, 13, the piezoelectric layer rests on a support substrate 11. Piezoelectric layer 10 is monocrystalline; indeed, excellent crystalline quality is required in order that no attenuation is caused to the surface wave.

Figure 2 is a functional view of a bulk acoustic wave resonator.

25 The resonator includes a thin piezoelectric layer (i.e. generally less than 1 μm thick, preferably less than 0.2 μm thick) and two electrodes 12, 13 installed either side of said piezoelectric layer 10 which, due to the method of manufacture according to the invention, is monocrystalline. Piezoelectric layer 10 rests on a support substrate 11. To isolate the resonator from the substrate and by this means prevent waves propagating in the
30 substrate, a Bragg mirror 14 is interposed between electrode 13 and substrate 11. In an alternative manner (not illustrated), this isolation could be accomplished by making a cavity between the substrate and the piezoelectric layer. These various arrangements are known to those skilled in the art, and will not therefore be described in detail in the present
35 text.

In a general manner, the invention proposes the formation of the monocrystalline layer, in particular a piezoelectric layer, by means of epitaxy on a material of a donor substrate, used as a seed for the epitaxy, until the desired thickness is obtained for the monocrystalline layer, and of a transfer to a receiver substrate, where said transfer can be
5 accomplished before the epitaxy (in which case a surface layer of the donor substrate, called the seed layer, is transferred on to the receiver substrate), or after epitaxy (in which case at least a proportion of the epitaxial layer is transferred on to the receiver substrate).

The donor substrate can be a homogeneous monocrystalline substrate of the material in question. Alternatively, the donor substrate can be a composite substrate, i.e.
10 in the form of a stack of at least two layers of different materials, a surface layer of which consists of the monocrystalline material in question.

Among the piezoelectric materials of particular interest are the perovskites and similar materials, of structure ABO_3 . However, the interest which these materials may hold is not limited to their piezoelectric character. In particular for other applications, for
15 example applications relating to integrated optics, they may possibly also be of interest due to their dielectric permittivity, their refraction indices, or alternatively their pyroelectric, ferroelectric or alternatively ferromagnetic properties, for example, as applicable.

A large family emerges. It is derived in particular from binary materials, such as $LiNbO_3$, $LiTaO_3$, $KNbO_3$, $KTaO_3$, leading to a general formula of the ABO_3 type, where A
20 consists of one or more of the following elements: Li, Na, K, H, and where B consists of one or more of the following elements: Nb, Ta, Sb, V.

To summarise, it will be considered that A consists of one or more of the following elements: Li, Na, K, H, and B consists of one or more of the following elements: Nb, Ta, Sb, V.

25 The receiver substrate acts as a mechanical support of the seed layer. It can be of any kind suitable for implementation of epitaxy (in particular in terms of stability of performance at high temperature), and advantageously, but not imperatively, suitable for the application in question. It can be homogeneous or composite.

At least one intermediate layer can be inserted between the receiver substrate and
30 the seed layer. For example, such an intermediate layer can be electrically conducting or electrically insulating. Those skilled in the art will be able to choose the material and the thickness of this layer according to the properties which they wish the radiofrequency device intended to include the piezoelectric layer to have.

Advantageously, the receiver substrate can be made of a semiconductor material. This can be, for example, a silicon substrate. This conducting material includes an intermediate layer of the "trap-rich" type, which can either be formed on the receiver substrate, or formed on the surface of the receiver substrate. The said intermediate layer of the trap-rich type is thus located between the seed layer and the receiver substrate, and enables the electrical insulation properties of the receiver substrate to be improved. The said intermediate layer of the trap-rich type can be formed by at least one of the materials of the polycrystalline, amorphous or porous types, in particular polycrystalline silicon, amorphous silicon or porous silicon, although is not restricted to these materials. In addition, depending on the stability of performance at high temperature of the intermediate layer of the trap-rich type for accomplishing epitaxy, it may be advantageous to introduce an additional layer between the receiver substrate and the said intermediate layer of the trap-rich type, to prevent its recrystallisation during a heat treatment.

According to a first implementation, the method includes a transfer of the seed layer of a donor substrate on to a support substrate, followed by the above-mentioned step of epitaxy. In this case the material of the seed layer is advantageously a material of composition ABO_3 , where A consists of at least one element from among: Li, Na, K, H, and B consists of at least one element from among: Nb, Ta, Sb, V. According to one implementation, both A and B consist of a single element. For example, the formula of ABO_3 can be $Li_{x1}K_{1-x1}Nb_{y1}Ta_{1-y1}O_3$, where $x1 = 0$ or 1 and $y1 = 0$ or 1 . Two very widely used representatives of this family of materials are $LiNbO_3$ and $LiTaO_3$. To a lesser extent, substrates $KNbO_3$ and $KTaO_3$ are also available. In the present text such a composition is called a binary composition. Such a binary material is generally manufactured by drawing in the form of an ingot. In this case the composition of the epitaxial layer is advantageously different from the composition of the seed layer, of the $A'B'O_3$ type, where A' consists of one or more of the following elements: Li, Na, K, H; B' consists of one or more of the following elements: Nb, Ta, Sb, V; A' is different from A or B' is different from B. To continue the previous example, the formula of $A'B'O_3$ can be $Li_{x2}K_{1-x2}Nb_{y2}Ta_{1-y2}O_3$, where $0 \leq x2 \leq 1$ and $0 \leq y2 \leq 1$ and where $x2$ is different from $x1$ or $y2$ is different from $y1$.

In the present text, if the total number of elements comprising A and B is equal to 3 such a composition is called ternary; if the total number of elements comprising A' and B' is equal to 4 such a composition is called quaternary. Unlike with binary materials, such ternary or quaternary materials are not, in the vast majority of cases, obtained by drawing an ingot, but must be obtained by epitaxy on a suitable support in order to be of sufficient quality for the desired dimensions.

In the first implementation a material of binary composition ABO_3 and a material of ternary (or higher order) composition $A'B'O_3$ will be preferred. More specifically, preference will be given to the preceding ABO_3 and $A'B'O_3$ compositions in which A' includes at least one element in common with A, and/or B' includes at least one element
 5 in common with B, where this element in common is advantageously the predominant one in the composition of A or B. In an even more preferred manner, the preceding ABO_3 and $A'B'O_3$ compositions will be chosen in which A' is identical to A when B' is different from B, and B' is identical to B when A' is different from A. A' may possibly be appreciably identical to A, or B' appreciably identical to B, when the content of a majority element of A
 10 or B varies slightly (for example, when A is Li and A' is $Li_{0.9}Na_{0.1}$, or alternatively when B is $Ta_{0.5}Nb_{0.5}$ and B' is $Ta_{0.6}Nb_{0.4}$).

According to a second implementation, the step of epitaxy is accomplished before the transfer step. In this case the donor substrate material serving as the seed for the epitaxy is a material of composition $A'B'O_3$, where A' consists of one or more of the
 15 following elements: Li, Na, K, H; B' consists of one or more of the following elements: Nb, Ta, Sb, V. In this case the composition of the epitaxial layer is of the $A''B''O_3$ type, where A'' consists of one or more of the following elements: Li, Na, K, H; B'' consists of one or more of the following elements: Nb, Ta, Sb, V. For example, the composition of the seed layer is $Li_{x1}K_{1-x1}Nb_{y1}Ta_{1-y1}O_3$, where $0 \leq x1 \leq 1$ and $0 \leq y1 \leq 1$ and the composition of the
 20 epitaxial layer is $Li_{x2}K_{1-x2}Nb_{y2}Ta_{1-y2}O_3$, where $0 \leq x2 \leq 1$ and $0 \leq y2 \leq 1$. The material of the epitaxial layer can be identical to that of the seed layer (in other words A' is identical to A'' and B' is identical to B'', i.e., in the above-mentioned example, $x1 = x2$ and $y1 = y2$). Alternatively, the material of the epitaxial layer is different from that of the seed layer (in other words A' is different from A'' or B' is different from B'', i.e., in the above-mentioned
 25 example, $x1$ is different from $x2$ or $y1$ is different from $y2$).

In the second implementation a material of binary composition $A'B'O_3$ and a material of ternary (or higher order) composition $A''B''O_3$ will be preferred. More specifically, preference will be given to the preceding $A'B'O_3$ and $A''B''O_3$ compositions in which A'' includes at least one element in common with A', and/or B'' includes at least one element
 30 in common with B', where this element in common is advantageously the predominant one in the composition of A or B. In an even more preferred manner, the preceding $A'B'O_3$ and $A''B''O_3$ compositions will be chosen in which A'' is identical to A' when B'' is different from B', and B'' is identical to B' when A'' is different from A'. A' may possibly be appreciably identical to A, or B' appreciably identical to B, when the content of a majority
 35 element of A or B varies slightly (for example, when A is Li and A' is $Li_{0.9}Na_{0.1}$, or alternatively when B is $Ta_{0.5}Nb_{0.5}$ and B' is $Ta_{0.6}Nb_{0.4}$).

According to a variant of the second implementation the method also includes, after the transfer step, the resumption of epitaxy on the transferred layer, so as to form a monocrystalline layer of composition $A'''B'''O_3$, where A''' consists of one or more of the following elements: Li, Na, K, H; B''' consists of one or more of the following elements: Nb, Ta, Sb, V. For example, the composition of the said additional epitaxial layer can be of the $Li_{x3}K_{1-x3}Nb_{y3}Ta_{1-y3}O_3$ type, where $0 \leq x3 \leq 1$ and $0 \leq y3 \leq 1$. $x3$ is preferably different from $x2$ or $y3$ is different from $y2$ (in other words, more generally, A''' is different from A'' or B''' is different from B'').

The invention thus enables, in particular, a thin layer of a compound $A'B'O_3$, $A''B''O_3$, or $A'''B'''O_3$, to be formed of excellent crystalline quality, and at least equal to that of the homogeneous substrates of the binary materials of this family, with a controlled thickness in a very wide range of thicknesses, and in particular for a thickness of less than 20 μm , and a large variety of properties which can be adjusted through the composition of the material.

The epitaxy can be accomplished by any appropriate technique, in particular by chemical vapour deposition (CVD), liquid phase epitaxy (LPE) or pulsed laser deposition (PLD), etc. With respect to the materials considered here reference may be made, for example, to publications [2], [3], [4], [5], [6].

Those skilled in the art will be able to determine the reagents and the operating conditions according to the material which must be grown, and the chosen technique.

The composition of the materials of the different layers is adjusted, through the choice of the elements constituting A , A' , A'' and/or A''' and B , B' , B'' and/or B''' and their stoichiometry in regard to the desired properties (for example, depending on the application: piezoelectric coupling factor, refraction index, etc.), but also taking into account the need to achieve consistency of the crystal lattice constants of the materials of the epitaxiated layers and their epitaxy support. The adaptation of lattice constants in the field of epitaxy is known to those skilled in the art.

It is understood that in addition to the various epitaxial layers described, additional epitaxial layers may be added, in particular buffer layers, intended to control the changes of the lattice constants, or of the stored stresses, or alternatively layers intended to provide selective etching stop layers.

The transfer of the seed layer (or, respectively, of the epitaxial layer) typically implies a step of bonding of the donor substrate and of the receiver substrate, as the seed layer (respectively epitaxial layer) is located at the bonding interface, followed by a step of thinning of the receiver substrate so as to expose the seed layer (respectively epitaxial layer).

In a particularly advantageous manner, the transfer is performed using the Smart Cut™ method, which is well known for the transfer thin semiconducting layers, particularly when made of silicon.

To this end, according to the first implementation, with reference to figure 3A, a
5 donor substrate 100 of a material of binary composition ABO_3 is provided, and a
embrittlement area 101 which delimits a monocrystalline layer 102 to be transferred,
intended to form the seed layer, is formed by ion implantation (represented
diagrammatically by the arrows). In this figure donor substrate 100 is represented as
homogeneous but, as mentioned above, it could alternatively be composite.
10 Advantageously, and depending on the piezoelectric material in question, the implanted
species are hydrogen and/or helium. Those skilled in the art will be able to determine the
dose and the implantation energy of these species to form the embrittlement area at a
determined depth, which is typically less than 2 μm : typically, and again depending on the
material and the implanted species in question, the dose is in the range 2×10^{16} to 2×10^{17}
15 ionic species/ cm^2 , and the implantation energy is 30 keV to 500 keV. The buried
embrittled layer can be obtained by any other means known to those skilled in the art, for
example by porosification of the material, or alternatively by laser irradiation.

With reference to figure 3B, donor substrate 100, embrittled in this manner, is
bonded on to receiver substrate 110, where the surface of the donor substrate through
20 which the implantation has been accomplished is at the bonding interface. Before bonding
the donor substrate and/or the receiver substrate may possibly be covered by an
electrically insulating or electrically conductive layer (not illustrated) which will have been
inserted between the receiver substrate and the seed layer after the transfer.

With reference to figure 3C, donor substrate 100 is detached along embrittlement
25 area 101. Such detachment can be accomplished by any means known to those skilled in
the art, for example thermal, mechanical or chemical means, etc. The remainder of the
donor substrate is then recovered, and may possibly be recycled, enabling layer 102 to be
transferred on to receiver substrate 110.

With reference to figure 3D, a surface portion of transferred layer 102 can optionally
30 be removed, for example by mechanical polishing and/or by chemical etching. The
purpose of this removal of material is to eliminate any defects relating to the implantation
and to the detachment in proximity to the embrittlement area. After this removal a thinned
layer 102 is obtained on receiver substrate 110, which will act as the seed layer for the
following epitaxy step. Alternatively, transferred layer 102 of figure 3C can be used directly
35 as the seed layer for the epitaxy.

With reference to figure 3E, a monocrystalline layer 103 of composition $A'B'O_3$ is made to grow by epitaxy on seed layer 102, where the material of epitaxial layer 104 is different to that of seed layer 102. Seed layer 102 thus imposes its lattice constant and allows a high-quality monocrystalline material to be grown. Growth stops when the thickness desired for the monocrystalline layer is reached. Final layer 10 is formed from the stack of seed layer 102 and epitaxial layer 103. The composition of epitaxial layer 103 may vary at different depths within it, either gradually or discontinuously.

As can be seen in figure 3E, after the method which has just been described, a substrate for a surface acoustic wave device or a bulk acoustic wave device is obtained which includes a receiver substrate 110 and a monocrystalline layer 10 on the said receiver substrate 110.

Layer 10 includes:

- a first portion 102 at the interface with receiver substrate 110, corresponding to the seed layer,
- a second portion 103 extending from first portion 102, corresponding to the epitaxial layer, made of a material of composition $A'B'O_3$, where the said material can be at least ternary.

This substrate is advantageously used to manufacture a surface acoustic wave device as illustrated in figure 1, or a bulk acoustic wave device as illustrated in figure 2, or alternatively other devices for microelectronics, photonics or integrated optics.

The seed layer is typically less than 2 μm thick, and preferably less than 1 μm thick.

The thickness of the epitaxial layer depends on the specifications of the device intended to incorporate the monocrystalline layer. With this regard, the thickness of the epitaxial layer is not limited either in terms of minimum value or of maximum value. Purely for information, the table below gives combinations of thicknesses of the seed layer and of the epitaxial layer:

Seed layer	0.5 μm	0.05 μm	0.1 μm	0.03 μm
Epitaxial layer	2.5 μm	0.95 μm	5 μm	0.15 μm

Figures 4A to 4E illustrate the main steps of the method according to the second implementation, in which epitaxy is implemented before transfer.

With reference to figure 4A a donor substrate 100 is provided, including a piezoelectric material of composition $A'B'O_3$. The said donor substrate can be homogeneous (as illustrated in figure 4A) or composite; in the latter case it includes a surface layer of composition $A'B'O_3$. This is the case in particular when the said material is at least ternary, if there are no ingots consisting of such material. A monocrystalline layer 103 of composition $A''B''O_3$ is then made to grow, by epitaxy, on the said material $A'B'O_3$, the material of composition $A'B'O_3$ being used as the seed for the epitaxy. The material of epitaxial layer 103 can be identical to or different from the material of donor substrate 100.

An embrittlement area is then formed in an embrittlement area in donor substrate 100 or in epitaxial layer 103 of composition $A''B''O_3$, so as to delimit a layer which is to be transferred. The embrittlement area can be formed by implantation of ionic species (shown diagrammatically by the arrows in figure 4B).

5 In the example illustrated in figure 4B embrittlement area 101 is formed in donor substrate 100, under epitaxial layer 103. The layer which is to be transferred, in this case, consists of the whole of epitaxial layer 103 and a portion 100' of donor substrate 100.

10 According to another implementation (not illustrated) the embrittlement area is formed in layer 103. The layer which is to be transferred, in this case, consists of the portion extending between the free surface of layer 103 and embrittlement area 101.

With reference to figure 4C, the donor substrate is bonded on to receiver substrate 110, epitaxial layer 103 of composition $A''B''O_3$ being at the bonding interface.

15 With reference to figure 4D, donor substrate 100 is detached along embrittlement area 101 so as to recover the remainder of the donor substrate, and to transfer the layer consisting of stack 103, 100' on to receiver substrate 110.

With reference to figure 4E, at least a surface portion of the transferred layer is removed. The purpose of this removal is to eliminate at least portion 100', and possibly a portion of layer 103, so as to expose the material of composition $A''B''O_3$.

20 Layer 103 obtained in this manner can then be used to manufacture a surface acoustic wave or bulk acoustic wave device.

25 According to a variant of this second implementation an additional step is performed, illustrated in figure 4F, consisting of a resumption of epitaxy implemented on layer 103 of composition $A''B''O_3$, so as to form an additional monocrystalline layer 104 of composition $A'''B'''O_3$. The material of the said additional layer 104 can be identical to that of layer 103, in which case this latter step of epitaxy results in a thickening of layer 103 (layer 104 is diagrammatically represented separately from layer 103 only so that it can be shown, but is not separate in the final layer, except possibly by its quality). Alternatively, additional layer 104 is made from a material different from that of layer 103.

The thickness of layer 103 and, if applicable, of layer 104, is chosen according to the specifications of the radiofrequency device intended to incorporate the said layer. The thickness of layer 103 is typically between 0.05 and 2 μm . The thickness of layer 104 is typically between 0.5 and 20 μm .

5 Whichever implementation is concerned, as an alternative (not illustrated) to the Smart Cut™ method, the transfer can be performed, after bonding of the donor substrate and the receiver substrate, through the removal of material, for example by mechanical polishing and/or chemical etching of the donor substrate until the seed layer is exposed. This variant is less advantageous as it involves consumption of the donor substrate,
10 whereas the Smart Cut™ method allows possible recycling of the donor substrate. Conversely, this variant requires no implantation within the donor substrate.

As can be seen in figures 4E and 4F, after the method according to the second implementation a substrate for a surface acoustic wave device or a bulk acoustic wave device is obtained which includes a receiver substrate 110 and a monocrystalline layer
15 103 of composition $A''B''O_3$ on said receiver substrate 110 and, if applicable, a layer 104 of composition $A'''B'''O_3$ on layer 103.

This substrate is advantageously used to manufacture a surface acoustic wave device as illustrated in figure 1, or a bulk acoustic wave device as illustrated in figure 2, where layer 103 or, if applicable, both layers 103 and 104, correspond(s) to layer 10 of
20 figures 1 and 2, or alternatively all other microelectronic, photonic or optical devices including a layer.

In certain cases it is possible for the receiver substrate on which the epitaxial growth occurs not to be optimal for the final application. Since the receiver substrate will be subjected to the operating conditions of epitaxy there is in fact a limited choice of suitable
25 materials. In particular, the receiver substrate cannot contain layers or elements which may be damaged by the epitaxy temperature. It can then be advantageous to transfer layer 10 on to a final substrate 111 the properties of which are chosen according to the sought application, by bonding it on to said substrate 111 through the surface of epitaxial layer 103 (cf. figure 5A) (or 104 if applicable), and by removing the receiver substrate (cf.
30 figure 5B). This transfer can be performed by any transfer technique described above. Another advantage of this transfer on to a final substrate is that seed layer 102, which was buried in the structure produced from epitaxy, is then exposed, and can be removed if needed (cf. figure 5C), in particular if it has defects. Only epitaxial layer 103 (and, if applicable, layer 104) (or a portion of the said layer) having the desired characteristics
35 then remains on final substrate 111.

If it is desired to manufacture a surface acoustic wave device, metal electrodes 12, 13 in the form of two interdigitated combs are deposited on the surface of layer 10 opposite receiver substrate 110 or, if applicable, the final substrate (whether this concerns receiver substrate 110 or final substrate 111, the said substrate forms the support substrate noted 11 in figure 1).

If it is desired to manufacture a bulk acoustic wave device, the method described above must be adapted accordingly. Firstly, before the step of bonding illustrated in figure 3B, a first electrode is deposited on the free surface of layer 102 which is to be transferred from the donor substrate, and this first electrode (referenced 13 in figure 2) is buried in the final stack. After the step of epitaxial growth illustrated in figure 3E a second electrode (referenced 12 in figure 2) is deposited on the free surface of layer 10, opposite the first electrode. Another option is to transfer the layer on to a final substrate, as mentioned above, and to form the electrodes before and after the said transfer. Secondly, to prevent acoustic waves propagating in receiver substrate 110 a means of isolation can be integrated in this substrate which can be, for example, a Bragg mirror (as illustrated in figure 2) or a cavity previously etched in substrate 110 or in final substrate 111, if applicable.

Whichever implementation is chosen the method according to the invention enables a monocrystalline layer to be formed which is not only binary but also ternary or quaternary, and thus allows a larger choice of properties for the said layer than materials traditionally used for surface acoustic wave or bulk acoustic wave devices. By this means a satisfactory compromise between the coupling coefficient and the electromechanical efficiency of the piezoelectric material can be obtained more easily.

Another field of application where the development of such solutions of piezoelectric materials is of particular interest is that of micro-sensors and micro-actuators. In the case of micro-sensors the purpose will in general be to measure a deformation caused by an external stress. In the case of micro-actuators, conversely, it will be sought to cause deformation of an element or motion of a moving part by application of an electric field, whether continuous or variable. Use of the piezoelectric material enables mechanical deformation and an electric signal to be linked. In the field of acoustics, for example, the external stress is a pressure wave which deforms a membrane. It can be within the audible spectrum, and objects which may typically be of interest are microphones (in sensor mode) and loudspeakers (in actuator mode). It can go beyond audible frequencies, for example for the production of Piezo Micromachined Ultrasonic Transducers (PMUT). It may also concern static pressure sensors or alternatively inertial sensors (acceleration sensors, gyroscopes, etc.), for which the motion of a moving mass which moves under the effect of acceleration is measured by means of the piezoelectric material. The piezoelectric material comprises the entire deformed element (membrane, beam,

cantilever, etc.), or advantageously only a portion of it, by stacking it with other materials such as silicon, for example, in order to ensure improved mechanical properties of the deformable portion. In the actuators category, piezoelectric materials can control a very precise movement and can be used, for example, to expel the ink from printer cartridges,
 5 or from micro-fluid systems, or alternatively to adjust a focal distance of an optical microsystem.

REFERENCES

- [1] W. Steichen and S. Ballandras, "Acoustic components used for filtering –
 10 Review of the different technologies", *Techniques de l'Ingénieur*, E2000, 2008
- [2] Doctoral thesis (Dipl. Phys. ETH Zurich), " $K_{1-y}Na_yTa_{1-x}NbO_3$ thin film Electro-optics" (Diss. ETH No. 17275)
- [3] L. S. Hung, J. A. Agostinelli, J. M. Mir, and L. R. Zheng, "Epitaxial nonlinear optical films of LiTaO₃ grown on GaAs in waveguide form", *Appl. Phys. Lett.* 62 (24), 14
 15 June 1993, p 3071
- [4] E. Dogheche and D. Remiens, S. Shikata, A. Hachigo, and H. Nakahata , "High-frequency surface acoustic wave devices based on LiNbO₃/diamond multilayered structure", *APPLIED PHYSICS LETTERS* 87, 213503, 2005
- [5] A. Bartasyte, V. Plausinaitiene, A. Abrutis, T. Murauskas, P. Boulet, S.
 20 Margueron, J. Gleize, S. Robert, V. Kubilius, and Z. Saltyte, "Residual stresses and clamped thermal expansion in LiNbO₃ and LiTaO₃ thin films", *APPLIED PHYSICS LETTERS* 101, 122902 (2012)
- [6] Letters to Nature, *Nature* 432, 84-87 (4 November 2004) doi: 10.1038/nature03028; "Lead-free piezoceramics", Yasuyoshi Saito, Hisaaki Takao,
 25 Toshihiko Tani, Tatsuhiko Nonoyama, Kazumasa Takatori, Takahiko Homma, Toshiatsu Nagaya & Masaya Nakamura

CLAIMS

1. Method of manufacturing a monocrystalline layer (10), characterised by the fact that it includes the following successive steps:
 - 5 - provision of a donor substrate (100) comprising a piezoelectric material of composition ABO_3 , where
 - A consists of at least one element from among: Li, Na, K, H;
 - B consists of at least one element from among: Nb, Ta, Sb, V;
 - supply of a receiver substrate (110),
 - 10 - transfer of a layer (102) called the "seed layer" from the donor substrate (100) on to the receiver substrate (110), by bonding the donor substrate on the receiver substrate such that the seed layer (102) is at the bonding interface, followed by thinning of the donor substrate (100) as far as the said seed layer (102);
 - growth, by epitaxy on piezoelectric material ABO_3 of the seed layer (102), of a
 - 15 monocrystalline layer (103) of composition $A'B'O_3$, where:
 - A' consists of a least one of the following elements: Li, Na, K, H;
 - B' consists of a least one of the following elements: Nb, Ta, Sb, V;
 - A' is different from A or B' is different from B.
- 20 2. Method according to claim 1, characterised by the fact that A' includes at least one element in common with A, and/or B' includes at least one element in common with B.
3. Method according to claim 1, characterised by the fact that A' is identical to A when B' is different from B, and by the fact that B' is identical to B when A' is different from
- 25 A.
4. Method according to one of the previous claims, in which A consists of a single element and B consists of a single element.
- 30 5. Method according to one of the previous claims, in which the transfer of the seed layer (102) includes the following steps:
 - formation of an embrittlement area (101) in the donor substrate (100) so as to delimit a layer, called the seed layer, containing the said piezoelectric material of composition ABO_3 ,
 - 35 - bonding of the donor substrate (100) on the receiver substrate (110), where the seed layer (102) is at the bonding interface,

- detachment of the donor substrate (100) along the embrittlement area (101) so as to transfer the seed layer (102) on to the receiver substrate (110).

6. Method according to claim 5, in which, before the step of epitaxy, a proportion of the thickness of the seed layer (102) transferred on to the receiver substrate (110) is removed.

7. Method according to one of claims 1 to 6, in which the thickness of the seed layer (102) is less than 2 μm , and preferably less than 1 μm .

8. Method according to one of the previous claims, characterised by the fact that the receiver substrate is made of a semiconductor material, and includes an intermediate charge-trapping layer between the seed layer and the receiver substrate.

9. Method of manufacturing a monocrystalline layer, characterised by the fact that it includes the following successive steps:

- provision of a donor substrate (100) comprising a piezoelectric material of composition $A'B'O_3$, where

A' consists of one or more of the following elements: Li, Na, K, H;

20 B' consists of one or more of the following elements: Nb, Ta, Sb, V;

- growth by epitaxy on the said piezoelectric material $A'B'O_3$ of a monocrystalline layer (103) of composition $A''B''O_3$, where

A'' consists of one or more of the following elements: Li, Na, K, H;

B'' consists of one or more of the following elements: Nb, Ta, Sb, V;

25 - supply of a receiver substrate (110),

- transfer of at least a proportion of the epitaxial layer (103) of composition $A''B''O_3$ on to the receiver substrate (110) by bonding of the donor substrate (100) on the receiver substrate (110) through the said epitaxial layer (103), followed by thinning of the donor substrate (100) as far as the said epitaxial layer (103) of composition $A''B''O_3$.

10. Method according to claim 9, including, after layer (103) of composition $A''B''O_3$ has been transferred on to the receiver substrate, growth, by epitaxy, on the said material of composition $A''B''O_3$, of a monocrystalline layer (104) of composition $A'''B'''O_3$, where

A''' consists of one or more of the following elements: Li, Na, K, H;

35 B''' consists of one or more of the following elements: Nb, Ta, Sb, V.

11. Method according to claim 10, in which A''' is different from A'' or B''' is different from B''.

12. Method according to one of claims 9 to 11, in which the transfer of the said at
5 least proportion of the epitaxial layer (103) of composition A''B''O₃ on to the receiver substrate (110) includes the following steps:

- formation of an embrittlement area (101) in the donor substrate (100) or in the epitaxial layer (103) of composition A''B''O₃, so as to delimit a layer which is to be transferred,
- 10 - bonding of the donor substrate (100) on to the receiver substrate (110), where the epitaxial layer (103) of composition A''B''O₃ is at the bonding interface;
- detachment of the donor substrate (100) or of the epitaxial layer (103) along the embrittlement area (101).

13. Method according to claim 12, in which the embrittlement area (101) is formed
15 in the donor substrate (100) and, after the transfer step, the transferred layer (100', 103) is thinned so as to expose the material of composition A''B''O₃.

14. Method according to one of claims 9 to 13, in which A'' is different from A' or B''
20 is different from B'.

15. Method according to one of claims 9 to 13, characterised by the fact that A'' includes at least one element in common with A', and/or B'' includes at least one element in common with B'.

25

16. Method according to one of claims 9 to 13, characterised by the fact that A'' is identical to A' when B'' is different from B', and by the fact that B'' is identical to B' when A'' is different from A'.

17. Method according to one of claims 9 to 16, in which A' consists of a single
30 element and B' consists of a single element.

18. Method according to either of claims 5 or 12, in which the embrittlement area (101) is formed by ion implantation in the donor substrate (100).

35

19. Method according to one of claims 1 to 18, in which after the step of epitaxy the thickness of monocrystalline layer (103) of composition $A''B''O_3$ is between 0.2 and 20 μm .

5 20. Method according to one of claims 1 to 19, in which at least one electrically insulating layer and/or at least one electrically conducting layer is formed at the interface between the receiver substrate and the donor substrate.

21. Method according to one of claims 1 to 20, including the transfer of at least a
10 proportion of the monocrystalline layer (103, 104) of the receiver substrate on to a final substrate (111).

22. Substrate for a microelectronic, photonic or optical device, characterised by the fact that it includes a support substrate (110) and a monocrystalline layer (103) of
15 composition $A''B''O_3$ on the said support substrate, where

A'' consists of one or more of the following elements: Li, Na, K, H;

B'' consists of one or more of the following elements: Nb, Ta, Sb, V;

at at least one of A'' and B'' consists of at least two elements,

and a layer (102) of composition $A'B'O_3$, where

20 A' consists of at least one element from among: Li, Na, K, H, and

B' consists of at least one element from among: Nb, Ta, Sb, V,

between the support substrate (110) and the layer (103) of composition $A''B''O_3$.

23. Substrate according to claim 22, also including, on the layer (103) of
25 composition $A''B''O_3$, a monocrystalline layer (104) of composition $A'''B'''O_3$, where

A''' consists of one or more of the following elements: Li, Na, K, H;

B''' consists of one or more of the following elements: Nb, Ta, Sb, V.

24. Method of manufacturing a surface acoustic wave device including the
30 deposition of electrodes (12, 13) on the surface of a monocrystalline piezoelectric layer (10), characterised by the fact that it includes the manufacture of the said piezoelectric layer by a method according to one of claims 1 to 21.

25. Surface acoustic wave device characterised by the fact that it includes a
35 monocrystalline piezoelectric layer (10) which can be obtained by a method according to one of claims 1 to 21, and two electrodes (12, 13) installed on the surface of the said monocrystalline piezoelectric layer.

26. Method of manufacturing a bulk acoustic wave device including the deposition of electrodes (12, 13) on two opposite faces of a monocrystalline piezoelectric layer (10), characterised by the fact that it includes the manufacture of the said piezoelectric layer by a method according to one of claims 1 to 21.

5

27. Bulk acoustic wave device characterised by the fact that it includes a monocrystalline piezoelectric layer (10) which can be obtained by a method according to one of claims 1 to 21, and two electrodes (12, 13) installed on two opposite faces of the said monocrystalline piezoelectric layer.

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28. Micro-sensor designed to measure a deformation caused by an external stress, characterised by the fact that it includes a monocrystalline piezoelectric layer (10) which can be obtained by a method according to one of claims 1 to 21.

15

29. Micro-actuator designed to cause a deformation of an element or motion of a moving part, through the application of a continuous or variable electric field, characterised by the fact that it includes a monocrystalline piezoelectric layer (10) which can be obtained by a method according to one of claims 1 to 21.