

METHOD FOR MANUFACTURING A HYBRID STRUCTURE

FIELD OF THE INVENTION

This invention relates to the field of manufacturing hybrid structures, especially structures that comprise a layer of piezoelectric material.

TECHNOLOGICAL BACKGROUND OF THE INVENTION

In the field of acoustic surface wave or volume devices (respectively "SAW" for "Surface Acoustic Wave" and "BAW" for "Bulk Acoustic Wave" in the English terminology), the hetero-structures comprising a layer of lithium tantalate (LiTaO_3) disposed on a silicon substrate have a growing interest: on the one hand, because they are compatible with standard microelectronics equipment and methods thanks to their silicon support substrate, that offer growth opportunities and lower costs; on the other hand, because they have technical advantages, such as less dependence on temperature, the frequency response of SAW devices as explained in the article by K. Hashimoto, M. Radota and al., "Recent development of temperature compensated SAW devices", IEEE Ultrasound. Symp. 2011, pages 79 to 86, 2011. Symp. 2011, pages 79 to 86, 2011.

For example, LiTaO_3/Si hetero-structures may be prepared from the assembling through bonding and by molecular bonding of two LiTaO_3 and Si substrates, respectively. For the manufacture of acoustic wave devices on these hetero-structures, it is advantageous to be able to apply a temperature above 200°C , or 250°C , to allow the use of materials and processes that ensure good performance of the devices.

The holding of the bonding interface between the LiTaO_3 layer and the Si support substrate is one of the important

factors that manage the good mechanical strength of the structure in temperature and especially beyond 200°C.

It therefore appears important to reinforce the energy of the interface of the hetero-structure prior to the manufacturing steps of the acoustic wave device; in the case of a hetero-structure manufactured by bonding a layer onto a support substrate by molecular adhesion, the bonding interface may in particular be reinforced by applying a heat treatment in a temperature range around 200 to 300°C. There is therefore the issue of applying such heat treatment to the hetero-structure without damaging it because of the significant difference in coefficient of thermal expansion (CTE for "Coefficient of Thermal Expansion") according to the Anglo-Saxon terminology) of both materials.

On the other hand, when a hetero-structure with a very thin layer of LiTaO_3 is required (for example for the manufacture of volume acoustic wave devices), one solution is to transfer the said layer using the Smart Cut® method, including a fragile plan buried in a LiTaO_3 donor substrate by introducing light species such as hydrogen or helium, the direct bonding (by molecular adhesion) of this donor substrate onto a silicon support substrate, and the detachment at the level of the fragile plan buried so as to transfer a superficial layer of LiTaO_3 on Si. It is known that the surface layer after transfer still has defects and light species in its thickness. It is therefore advantageous to cure this layer, to perform an annealing in a suitable temperature range: to allow the cure of defects and the evacuation of light species, but without damaging the qualities of the thin layer transferred or the mechanical strength of the hetero-structure. Example, for a layer of LiTaO_3 , the suitable temperature range is between 400° and 600°C.

The issue again is that the LiTaO_3/Si hetero-structures, given the very large difference in coefficient of thermal expansion between the two materials, hardly support these high thermal budgets.

During the manufacture of hybrid structures or hetero-structures, it is customary to carry out heat treatments having a high temperature when the surface layer disposed on the support substrate is as thin as possible, so as to limit stresses and deformations (as can be noticed in a curvature of the substrate) in the said hybrid structure. For instance, one can mention hybrid structures of silicon type on solid silica or silicon on sapphire, which can withstand annealing to the tune of 850°C when the thickness of the silicon surface layer is less than about 100 nm., and the thickness of the massive silica substrate is about 700 microns, without suffering prohibitive damage. For higher thicknesses of the surface layer, typically 1 micron, the maximum applicable temperature without damage decreases for example to around 600°C . For even much higher thicknesses of the upper layer, for example 700 microns, the maximum applicable temperature without damage decreases for example around $100\text{--}150^\circ\text{C}$.

For a hybrid structure composed of a layer of LiTaO_3 (for example 10 microns thick) disposed on a silicon substrate (for example 150 mm in diameter and 625 microns thick), the applicant used this knowledge of state of the art: it applied the annealing temperature required to reinforce the bonding interface (i.e., 250°C) to the final hybrid structure (10 microns LiTaO_3 over 625 microns Si), that is with the finest possible surface layer. The Applicant then observed unexpected results: a significant degradation of the layer by a so-called "buckling" phenomenon corresponding to the local buckling deformation of the LiTaO_3 layer, rendering the hybrid structure unusable.

PURPOSE OF THE INVENTION

Embodiments of the invention therefore seek to propose a method of manufacturing a hybrid structure and find a solution to the disadvantages of the former art. Embodiments of the invention seek to propose a method for applying a required heat treatment without damaging the hybrid structure.

BRIEF DESCRIPTION OF THE INVENTION

An aspect of the invention provides a method of manufacturing a hybrid structure comprising an effective layer of piezoelectric material that has an effective thickness disposed on a support substrate with a support thickness and a coefficient of thermal expansion less than that of the effective layer. The method comprises:

a) A step of providing a bonded structure comprising a donor substrate of piezoelectric material and the support substrate, the bonded structure having a bonding interface between these two substrates;

b) A first step of thinning the donor substrate to form a thinned layer, having an intermediate thickness, disposed on the support substrate; the assembly forming a thinned structure;

c) A heat treatment step of the thinned structure at an annealing temperature;

d) A second thinning step, after step c), of the thinned layer to form the effective layer;

the method being remarkable in that it comprises, prior to step b), a step a') of determining a range of intermediate thicknesses avoiding a degradation of the thinned structure (6') during the step c), the range being defined by a threshold

thickness and a maximum thickness, and the intermediate thickness of the thinned layer being chosen in this range. The threshold thickness and the maximum thickness are determined respectively from a first sensitivity model and a second sensitivity model. The first sensitivity model is associated with a relaxation of the thinned layer in compression on the support substrate and the second sensitivity model is associated with rupture of the support substrate, constrained in extension by the thinned structure during the heat treatment.

The manufacturing method according to the invention thus makes it possible to apply a heat treatment to an annealing temperature required to consolidate the bonding interface or to cure all or part of defects present in the thinned layer (which will become the effective layer), to a thinned structure for which the range of compatible thicknesses of the thinned layer has been previously determined. The said heat treatment is generally not applicable to the final hybrid structure, that is with the effective layer to its effective thickness, without generating damage to the effective layer, especially when unglued areas (bonding defects or pre-existing engraved patterns on the assembled faces of the substrates) are found at the bonding interface

according to advantageous features of the invention, taken alone or in combination:

- • The threshold thickness is determined from a first sensitivity model whose input parameters include the support thickness, the thermal expansion coefficients of the donor substrate and of the support substrate, the annealing temperature and a maximum size of unglued areas found at the bonding interface of the bonded structure;

- The maximum thickness is determined from a second sensitivity model whose input parameters include the support thickness (of the support substrate 1), the thermal expansion coefficients of the donor substrate 2 and the support substrate 1 and the required annealing temperature in step c) heat treatment.
- The manufacturing process comprises, after step a') and prior to step b), a step a'') of recycling the bonded structure, when the determining step a') establishes the

upper threshold thickness at maximum thickness or maximum thickness lower than the effective thickness;

- Recycling step a'' comprises a separation at the bonding interface of the bonded structure;
- 5 • Recycling step a'') comprises the reuse of the donor and support substrates resulting from the separation for a new step a) of providing a bonded structure;
- The second thinning step d) may further comprise a step of thinning the support substrate;
- 10 • The effective layer is composed of a material chosen from: lithium tantalate (LiTaO_3), lithium niobate (LiNbO_3), aluminium nitride (AlN), zinc oxide (ZnO);
- The support substrate is composed of a material chosen from the group: silicon, III-V semiconductors, silicon carbide, 15 glass, sapphire;
- The support substrate comprises one or more surface layers.

There is also disclosed a hybrid structure comprising an effective layer of piezoelectric material with an effective thickness of less than 50 microns assembled to a support 20 substrate having a coefficient of thermal expansion less than that of the effective layer, the hybrid structure being characterized in that a bonding interface between the effective layer and the support substrate has a bonding energy greater than 1000 mJ/m² and at least one non-bonded zone whose 25 size is between 1 and 1000 microns.

BRIEF DESCRIPTION OF THE DRAWINGS

Other characteristics and advantages of the invention will emerge from the detailed description of the invention which follows in the References to the accompanying drawings 30 in which:

Figures 1a to 1c show a method of manufacturing a hybrid structure according to the invention;

Figures 2a to 2c show three different configurations of thickness ranges, versus the effective thickness, resulting from a determination step according to the invention;

Figure 3 shows different stages of the manufacturing process according to the invention.

DETAILED DESCRIPTION OF THE INVENTION

The invention relates to a method for manufacturing a hybrid structure 60 comprising a effective layer 20 of piezoelectric material disposed on a support substrate 1 having a support thickness and a coefficient of thermal expansion less than that of the effective layer 20 (Figure. 1c).

The method comprises a step a) of providing a bonded structure 6 comprising a donor substrate 2 of piezoelectric material and the support substrate 1. Bonded structure 6 has a bonding interface 5 between these two substrates 1, 2 (Figure 1a). For example, the donor substrate 2 may be composed of a material chosen from the group: lithium tantalate (LiTaO_3), lithium niobate (LiNbO_3), aluminium nitride (ALN), zinc oxide (ZnO). The support substrate may be composed of a material selected from the group: silicon, III-V semiconductors, silicon carbide, glass, sapphire. One and/or the other of the substrates 1,2 may optionally comprise components (all or part of microelectronic circuits) or etched patterns on their face to be assembled: the components may be formed of stacked layers of different natures and having patterns; the etched patterns may be formed by cavities intended to ensure a function in the final device produced on the hybrid structure 60. The assembly of the bonded structure 6 is advantageously

made by molecular bonding between the donor substrate 2 and the substrate support 1. Optionally, an intermediate layer, such as a layer of silicon oxide, silicon nitride or other layer that enhance adhesion molecular bonding, may be added to one or both substrates before assembly. Advantageously, the substrates 1, 2 are also subjected to cleaning and/or front surface activation before assembly, to enhance the quality and energy of the bonding interface 5 formed after assembly.

The term "unglued zone" is henceforth called a localized zone at the bonding interface, at which the surfaces of the two substrates are not intimately in contact, with the exception of the unbonded peripheral crown at the edges of the assembled substrates that form an exclusion zone. An "unbonded area" is typically surrounded by a glued area. An unglued zone may be linked to a bonding defect, for example due to the presence of a particle or other contamination (hydrocarbon or other) at the bonding interface 5 of the bonded structure 6. It may also be related to the presence of an etched pattern or local topography on the donor substrate 2 or the support substrate 1, due to the presence of components or cavities or laser marks (for example to ensure the traceability of the substrates) on their respective faces to be assembled.

After the assembly step, the method comprises a step b) corresponding to a first step of thinning the donor substrate 2 to form a thin layer 2', with an intermediate thickness, disposed on the support substrate 1; the whole forming a thinned structure 6' (Figure 1b. The donor substrate 2 is thinned at its rear face 4, by techniques of mechanical thinning, mechanical-chemical and/or chemical etching or by a Smart Cut® type process, well known to those skilled in the art. For instance, the donor substrate 2 can be thinned by "grinding" (mechanical thinning) and then by chemical-mechanical polishing. This thinning step precedes a heat

treatment step c) the function of which may be to consolidate the bonding interface 5 or to cure defects in the thinned layer 2' which becomes the effective layer 20. It is thus important that the step b) thinning leads to obtaining a
 5 thinned structure 6' that is compatible with the heat treatment required in the following step c).

As such, the manufacturing method is remarkable in that it comprises a step a'), prior to step b) of thinning, of determining a range of intermediate thicknesses for the
 10 thinned layer 2', meant to avoid degradation of the thinned structure during step c) heat treatment. The said range is defined by a threshold thickness and a maximum thickness, the intermediate thickness of the thinned layer 2' is thus chosen in this range.

The threshold thickness is determined from a first sensitivity model whose input parameters include the support thickness (of the support substrate 1), the thermal expansion coefficients of the donor substrate 2 and the support substrate 1, the temperature of annealing required in step c)
 15 heat treatment and a maximum size of unbonded areas found at the bonding interface 5 of the bonded structure 6.

The first sensitivity model is established from an equation reflecting the relaxation of a thin layer in compression on a substrate. A phenomenon of relaxation of a
 25 thin layer such as "buckling" requires the presence of an unglued zone at the interface between the thin layer and the substrate. The buckling critical stress necessary to initiate the relaxing of the thin layer, which corresponds to the local buckling deformation of the said layer, can be expressed as:

$$\sigma_{buckling} = \frac{\pi^2 E_2}{12(1 - \nu_2^2)} \left(\frac{h_2}{r} \right)^2 \quad \{\text{equ.1}\}$$

with E_2 the Young's modulus of the thin layer, ν_2 the Poisson's ratio of the thin layer, h_2 the thickness of the thin layer and r the radius of the unbonded zone between the thin layer and the substrate. The stress translates a force applied per unit area over the section (length x thickness) of the thin layer. To overcome the length of the said section and to consider only the thickness h_2 of the thin layer, it is possible to express a critical force normalized by the length, in N/m: $F_{buckling}^{norm}$

$$F_{buckling}^{norm} = \sigma_{buckling} \cdot h_2 = \frac{\pi^2 E_2 \cdot h_2}{12(1-\nu_2^2)} \left(\frac{h_2}{r}\right)^2 \quad \{\text{equ.2}\}$$

Consider that the thin layer corresponds to the thinned layer 2': E_2 , ν_2 are therefore the Young's modulus and the Poisson's ratio respectively of the piezoelectric material that constitute the thinned layer 2'; h_2 is the intermediate thickness and r is the maximum radius of the non-bonded areas present at the bonding interface 5 of the bonded structure 6. The size of unbonded areas found at the bonding interface 5 may for example be determined by imaging in white light or infrared according to the materials that are part of the bonded structure 6, or by acoustic microscopy, especially advantageous technique for detecting unglued areas of small size. The maximum radius of the areas not bonded to the bonding interface 5 (which may be related to bonding defects or to pre-existing patterns on one or the other of the assembled faces of the donor 2 and support 1 substrates) may thus be taken out for each bonded structure 6.

The equation {equ.2} indicates that the "buckling" phenomenon will be all the easier to initiate (i.e., it will require a lower normalized force) than the intermediate

thickness h_2 of the thinned layer 2' will be weak and that the maximum radius r unglued areas will be large. $F_{buckling}^{norm}$

The support thickness h_1 of the support substrate 1 and its mechanical characteristics (E_1 , its Young's modulus) are also known; the required annealing temperature to be applied to the thinned structure 6' during the heat treatment of step c) is also known. It is therefore possible to express the force in normalized compression that will apply to the thinned layer 2' during the heat treatment of step c): F^{norm} .

$$F^{norm} = \frac{(E_1 \cdot h_1^3 + E_2 \cdot h_2^3)}{6(h_1 + h_2) \cdot \rho} \quad \{\text{equ.3}\}$$

with p the radius of curvature of the thinned structure 6:

$$\frac{1}{\rho} = \frac{\Delta CTE \cdot \Delta T}{K(h_1, h_2)} \quad \{\text{equ.4}\}$$

with ΔCTE , the difference between thermal expansion coefficients of the respective materials of the thinned layer 2' and the support substrate 1; ΔT delta temperature between room temperature and annealing temperature applied; and the term $K(h_1, h_2)$ which is expressed as:

$$K(h_1, h_2) = \frac{h_1 + h_2}{2} + \frac{(E_1 \cdot h_1^3 + E_2 \cdot h_2^3)}{6(h_1 + h_2)} \cdot \left(\frac{1}{E_1 \cdot h_1} + \frac{1}{E_2 \cdot h_2} \right) \quad \{\text{equ.5}\}$$

The threshold thickness of the range can thus be determined by solving the equation {equ.5} $F^{norm} = F_{buckling}^{norm}$

$$\frac{(E_1 \cdot h_1^3 + E_2 \cdot h_{2seuil}^3) \cdot \Delta CTE \cdot \Delta T}{6(h_1 + h_{2seuil}) \cdot K(h_1, h_{2seuil})} = \frac{\pi^2 E_2 \cdot h_{2seuil}}{12 (1 - \nu_2^2)} \left(\frac{h_{2seuil}}{r} \right)^2 \quad \{\text{equ.6}\}$$

with the said threshold thickness. h_{2seuil}

The threshold thickness corresponds to the intermediate thickness below which the "buckling" phenomenon has a high probability of appearing, taking into account the characteristics of the thinned structure 6' (type of materials that constitute it, maximum size of unglued zones found at the bonding interface 5, thickness of the support substrate) and the annealing temperature to be applied during step c) heat treatment. Note that the "buckling" phenomenon can also be accompanied by an enlargement of the unbonded zone, preferably perpendicular to the crystallographic axes having the highest coefficient of expansion. This enlargement can all the more be as significant as the energy of the bonding interface 5 is low. Consolidating the energy of the bonding interface 5, in a configuration to avoid the appearance of "buckling" is therefore of utmost importance.

The first sensitivity model thus connects the threshold thickness to a set of characteristic parameters of the thinned structure 6' and to the thermal stress it must undergo.

The maximum thickness is determined from a second sensitivity model whose input parameters include the support thickness (of the support substrate 1), the thermal expansion coefficients of the donor substrate 2 and the support substrate 1 and the required annealing temperature in step c) heat treatment.

The second sensitivity model is established from an equation reflecting the rupture of the material that constitutes support substrate 1, constrained in extension in the thinned structure 6' during a heat treatment. Elastic energy E stored in the support substrate 1, in the case of a thinned structure 6' comprising a thinned layer 2' and a support substrate 1 of different nature and to which a heat treatment is applied, is expressed as follows:

$$E = \frac{1}{E_1} \left(\frac{(P^{norm})^2}{h_1} + \frac{E_1^2 \cdot h_1^3}{12 \cdot \rho^2} \right) \quad \{\text{equ.7}\}$$

Rupture of the material that constitutes support substrate 1 appears when elastic energy E exceeds a critical value given by:

$$E_{rupture} = \frac{K_{1c}^2}{E_1}$$

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with Kic the tenacity of the material that constitutes support substrate 1.

The maximum thickness of the range can thus be determined by solving the equation: $E = E_{rupture}$,

$$\left(\frac{1}{h_1} \left[\frac{(E_1 \cdot h_1^3 + E_2 \cdot h_{2plafond}^3) \cdot \Delta CTE \cdot \Delta T}{6(h_1 + h_{2plafond}) \cdot K(h_1, h_{2plafond})} \right]^2 + \frac{E_1^2 \cdot h_1^3 \cdot (\Delta CTE \cdot \Delta T)^2}{12 \cdot [K(h_1, h_{2plafond})]^2} \right) = K_{1c}^2$$

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with the said maximum thickness. $h_{2plafond}$

The maximum thickness corresponds to the intermediate thickness of the thinned layer 2' above which the rupture of support substrate 1 has a high probability of appearing, taking into account the characteristics of the thinned structure 6' (type of material constituting it, thickness of the support substrate 1) and the annealing temperature to be applied during the thermal treatment of step c).

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The second sensitivity model thus connects the maximum thickness to a set of characteristic parameters of the thinned structure 6' and to the heat stress it must undergo.

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A heterogeneous structure such that thinned structure 6' undergoes stress and deformations when subjected to a heat treatment, due to the differential expansions of the two

materials that constitute it. It deforms by adopting a curvature that can lead to different failure modes: the breaking of the support substrate 1, the buckling of the thinned layer 2', the formation of dislocations or sliding planes in the structure (especially in thinned layer 2'), the lift-off at the edges of thinned structure 6', etc. Experimentally, the plaintiff realised that, in the case of thinned structures 6' comprising a layer of piezoelectric material and a support substrate of a material with a lower coefficient of thermal expansion, the two predominant failure modes were on the one hand the breakage of the support substrate 1 (rupture phenomenon of the material beyond the critical rupture energy) and secondly, the local buckling at the level of non-bonded areas of the thinned layer 2' (phenomenon of relaxation of a thin layer in compression, called "buckling"). The two sensitivity models established by the plaintiff from equations {equ.6} and {equ.9} are therefore well suited to determining thickness ranges for the thinned layer 2', in the case of heterogeneous thinned structures 6', the said thinned layer 2' of which is made up of a piezoelectric material.

Following step a'), a thickness range defined by the determined threshold thickness and maximum thickness is thus obtained, as illustrated in Figures 2a to 2c.

According to a first variant of implementing the manufacturing method, the effective thickness of the expected effective layer 20 for the final hybrid structure 60 is less than the defined thickness range (Figure 2a): this is a case of thicknesses ranges that are compatible with the envisaged final structure. The manufacturing method according to the invention comprises, as mentioned above, step b) of thinning of the donor substrate 2 to form the thinned layer 2', after step a') to determine the thickness range with which it is

compatible. The intermediate thickness of thinned layer 2' is then chosen to be in the said range, i.e., between the threshold thickness and the maximum thickness. The process then comprises step c) of heat treatment at the annealing temperature required for the thinned structure 6'. For instance, the annealing temperature may vary between 200°C and 600°C depending on the type of hybrid structure expected and according to the aim of the heat treatment: consolidating bonding interface 5, cure of defects or diffusion of light species in the thickness of thinned layer 2' (intended to become the effective layer 20), etc. Heat treatment may comprise an inlet and an outlet of the oven at a low temperature, for example 100°C, a rise and fall ramp in temperature, for example between 0.5 and 5°/min, and a bearing at the required annealing temperature, for example, between 200°C. and 600°C., for a period ranging from 30 min to a few hours.

After step c) of heat treatment, the method comprises a step d) corresponding to a second step of thinning the thinned layer 2' to form the effective layer 20 that has a effective thickness, disposed on support substrate 1; the whole forming the final hybrid structure 60 (Figure 1e). Layer 2' is thus thinned again, at its rear face 4, by techniques of mechanical thinning, mechanical-chemical and/or chemical etching and/or thinning by the Smart Cut® method. For instance, layer 2' can be thinned by mechanical-chemical polishing sequences, followed by cleaning. The hybrid structure 20 thus formed can then be used for the production of electronic devices, its properties (bonding energy of bonding interface 5 and/or quality of effective layer 20) having been improved by the realization of the method according to the invention. Usually, the development steps of devices do not require heat

treatments to be applied at a temperature as high as the annealing temperature of step c) of the method.

According to a second implementation variant of the manufacturing method, the effective thickness of the expected effective layer 20 for final hybrid structure 60 is within the defined thickness range (Figure. 2b); this is in a case of thickness range compatible with the envisaged final structure. The manufacturing method according to the invention comprises, as mentioned above, step b) of thinning the donor substrate 2 to form the thinned layer 2', after step a'). The intermediate thickness of the thinned layer 2' is advantageously chosen to be in the range, and especially, it is chosen to be equal to or substantially greater than the effective thickness. The process then comprises step c) of heat treatment at the annealing temperature required for the thinned structure 6'. For instance, the annealing temperature may vary between 200°C and 600°C depending on the type of hybrid structure 60 expected and according to the objective of the heat treatment.

After heat treatment in step c), the method comprises a step d) corresponding to a second step of thinning the thinned layer 2' to form the effective layer 20 with a effective thickness, disposed on support substrate 1; the whole forming the final hybrid structure 60. According to this second implementation variant, step b) of thinning the thinned layer already brings the intermediate thickness substantially to the effective thickness. Step d) can thus consist essentially of a polishing step with a low removal ("touch polishing" according to the English terminology) and cleaning sequences, to improve the surface condition of the face 4 of the effective layer 20. The hybrid structure 20 thus formed can then be used for the development of electronic devices, especially acoustic wave devices.

According to a third variant of implementing the manufacturing method according to the invention, the effective thickness of the effective layer 20 expected for the final hybrid structure 60 is greater than the defined thickness range (Figure 2c); in other words, the effective thickness is greater than the maximum thickness. This configuration reflects the fact that the defined thickness range (determined by the sensitivity models and from the characteristics of the bonded structure 6 and the required annealing temperature) is incompatible with the expected final hybrid structure 20.

This thickness range configuration that is incompatible with the expected hybrid structure (Figure 2c) can be as a result of the inadequacy of the support thickness. The manufacturing method, according to the invention, then comprises a step a'') of recycling the bonded structure 6. Step a'') consists of achieving the lift-off of the bonded structure 6 at the bonding interface 5, leading to the separation of the donor substrate 2 and the support substrate 1. The separation can be performed by inserting a bevel-shaped tool between the chamfered edges of the two donor and support 2 substrates 1 of the bonded structure 6. After the separation, the recycling step a'') further comprises the reuse of the detached donor and support 2 substrates for a new step a) to provide a bonded structure 6. One can take advantage of the recycling step a'') to use a support substrate 1 of greater thickness and provide a new bonded structure 6. The increase in the support thickness notably increases the value of the maximum thickness, the aim of which is to find a range of compatible thicknesses; i.e., with a maximum thickness greater than the expected effective thickness. The second thinning step d) according to the method also comprises, in this case, a thinning step of the rear face of the support substrate 1, so as to bring it back to the required support thickness for

the final hybrid structure 60. This additional thinning step may consist of a mechanical, mechanical-chemical or chemical thinning.

5 The configuration in which the thickness range is incompatible with the expected hybrid structure (Fig. 2c) may also be related to the fact that the annealing temperature is too high. One can then choose to reduce the annealing temperature to be applied in step c) of heat treatment. The recycling step a") can also be used to apply a different
10 surface preparation (potentially more complex or expensive but necessary in this case) to the substrates 1 and 2 before their assembly, allowing for example to promote the bonding energy after a heat treatment at a lower temperature. A new thickness range is then determined before continuing the process.

15 According to a fourth implementation variant of the manufacturing method, the threshold thickness determined in step a') is greater than the maximum thickness determined at the same step (configuration not shown). In this case, the thickness range is also considered incompatible with the
20 expected structure, since it does not exist (the thickness range being defined by a threshold thickness lower than a maximum thickness). It may be that in this case the maximum size of the unbonded areas found at the bonding interface 5 is too large to allow a compatible thickness range. The
25 manufacturing method, according to the invention, then comprises a step a'') of recycling the bonded structure 6. Step a'') consists of achieving the lift-off of the bonded structure 6 at the bonding interface 5, leading to the separation of the donor substrate 2 and the support substrate
30 1. The detachment can be done by applying a stress at the interface between the two donor substrates 2 and support 1 of the bonded structure 6. After the separation, the recycling step a'') comprises the reuse of the detached donor substrates

2 and support 1 for a new step a) of providing a bonded structure 6. Assuming that the unglued zone of maximum size was relative to a bonding failure, the recycling step a'') can eliminate this defect by a new cleaning and preparation of the surfaces of substrates 1,2 to be assembled.

If the size of the unbonded areas found at the bonding interface 5 is difficult to reduce (in the case, for example, of pre-existing patterns or cavities on one of the two substrates assembled and having a particular function), step a'') of recycling can be used for example to use and modify the assembly conditions in order to allow a reduction in subsequent temperature required to be applied in step c) and provide a new bonded structure 6.

The main steps of the method according to the invention are illustrated in (figure 3.)

The manufacturing method according to the invention makes it possible to apply a heat treatment to an annealing temperature required to consolidate the bonding interface 5 or to cure defects in the thinned layer 2' (which becomes the effective layer 20), a thinned structure 6' for which the range of compatible thicknesses for the thinned layer 2' has been previously determined. The said heat treatment is generally not applicable to the final hybrid structure 60 (i.e.) with the effective layer 20 to its effective thickness, without generating damage to the effective layer 20, especially when unglued areas (pre-existing bonding defects or engraved patterns on the assembled faces of the substrates 1, 2) are found at the bonding interface 5.

Besides, step a'') to determine the range of compatible thicknesses makes it possible to identify when it is necessary to recycle the bonded structure 6. This is before engaging the

thinning step b), which allows thus to increase the manufacturing yields.

The invention also relates to a hybrid structure 60 comprising an effective layer 20 of piezoelectric material of effective thickness less than 50 microns assembled to a support substrate 1 having a coefficient of thermal expansion less than that of the effective layer 20 (Figure 1e). The bonding interface 5 between the effective layer 20 and the support substrate 1 has a bonding energy greater than or equal to 1000 mJ/m² and at least one non-bonded area whose size is between 1 and 1000 microns. The effective layer 20 is composed of a material chosen from the group: lithium tantalate (LiTaO₃), lithium niobate (LiNbO₃), aluminium nitride (AlN), zinc oxide (ZnO); For example, its thickness is between 0.1 micron and 50 microns. The support substrate is made up of a material chosen from the group: silicon, III-V semiconductors, silicon carbide, glass, sapphire; For example, its thickness is between 0.1 micron and 50 microns. The support substrate can also comprise one or more different types of surface layers. For example, the support substrate may consist of a single-crystal silicon substrate having a surface layer on the side of its face to be assembled, capable of trapping charges, in particular polycrystalline silicon; it may also consist of a SOI substrate (silicon on insulator) whose surface layers are in silicon oxide and silicon or in a SOI substrate provided with a charge trapping layer under the oxide layer.

Example 1 :

A support substrate 1 made of silicon (Si) 150 mm in diameter, 725 microns thick, has etched patterns spaced evenly over its entire face to be assembled. These reasons may for example have a function of alignment marks or constitute cavities for the manufacture of suspended membranes or more

still made up of electrical contacts in the final hybrid structure 60, on which the devices is developed. The support substrate 1 also comprises an oxide layer on its face to be assembled. It is glued together by molecular bonding with a donor substrate 2 made of lithium tantalate (LiTaO_3) of the same diameter to provide the bonded structure 6. A microscopy acoustic control step makes it possible to detect and measure the non-bonded areas at the bonding interface 5, generated by the patterns. The maximum size of unglued areas corresponds to a radius r of 500 microns.

The expected final hybrid structure 60 has a useful 10 micron layer and a 725 micron support substrate. The annealing temperature to be applied is 250°C in order to sufficiently consolidate the bonding interface 5 so that the hybrid structure 60 supports the subsequent steps of developing the acoustic wave devices.

Step a') makes it possible to determine threshold and maximum thicknesses: $h_{2\text{threshold}} = 28 \mu\text{m}$ and $h_{2\text{ceiling}} = 32 \mu\text{m}$. The thickness range obtained is compatible with the expected hybrid structure 60, the effective thickness being less than the said range.

Step b) thinning, consisting of mechanical thinning followed by chemical mechanical polishing and chemical cleaning, allows the forming of a thinned layer 2' having an intermediate thickness of 30 microns. The heat treatment of step c) is then carried out. Entry into the oven is at 100°C , the ramp temperature rise is $1^\circ/\text{min}$ until it reaches a peak at 230°C , for a period of 4 hours. A temperature ramp down to $1^\circ/\text{min}$ is then operated up to 100°C before taking out the thinned structure 6' of the oven. The thinned structure 6' then undergoes a second step of thinning the thinned layer 2' to a thickness of 10 microns to form the effective layer 20.

The hybrid structure 60 thus obtained is integral and has a consolidated bonding interface 5 whose bonding energy is greater than or equal to 1000 mJ/m², a useful integrated layer having no degradation linked to "buckling" phenomena and this despite the presence of unglued areas at its interface, a size ranging between 100 and 500 microns. Such a hybrid structure 60 can then be used for the development of acoustic wave devices.

Example 2 :

A support substrate 1 made of silicon (Si) having a diameter of 150 mm and a thickness of 725 microns and comprising an oxide layer on its face to be assembled is adhesively bonded to a donor substrate 2 made of lithium tantalate (LiTaO₃) of the same diameter to provide the glued structure 6. A microscopy acoustic control step makes it possible to detect two gluing defects (unglued areas) at the gluing interface 5, whose maximum size corresponds to a radius r of 700 microns.

The expected final hybrid structure 60 has a useful 10 micron layer and a 725 micron support substrate. The annealing temperature to be applied is 250°C, with the aim of sufficiently consolidating the bonding interface 5 so that the hybrid structure 60 supports the subsequent steps of developing the acoustic wave devices.

Step a') makes it possible to determine threshold and maximum thicknesses: $h_{2\text{threshold}} = 28 \text{ }\mu\text{m}$ and $h_{2\text{ceiling}} = 25 \text{ }\mu\text{m}$. The thickness range obtained is not compatible with the expected hybrid structure 60, the threshold thickness being greater than the maximum thickness.

The recycling step a'') is then carried out, in order to reduce the maximum size of the gluing defects present at the

gluing interface 5: the insertion of a tool in the form of a bevel at the level of the bonding interface 5 of the bonded structure 6 makes it possible to separate the donor 2 and support 1 substrates. A new cleaning and surface activation sequence of the two substrates is carried out before a new assembly to provide a new bonded structure 6. A new acoustic microscopy control step makes it possible to detect ten defects at the bonding interface 5, the maximum size of which corresponds to a radius r of 150 microns.

On the basis of new characteristics of bonded structure 6, step a') helps to determine the following threshold and maximum thicknesses: $h_2 \text{ threshold} = 20 \text{ } \mu\text{m}$ and $h_2 \text{ ceiling} = 25 \text{ } \mu\text{m}$. The thickness range obtained is now compatible with the expected hybrid structure 60, the threshold thickness being less than the maximum thickness and the effective thickness being less than the said range.

Step b) of thinning, consisting of a mechanical thinning followed by chemical mechanical polishing and chemical cleaning, allows a thinned layer 2' whose intermediate thickness is 23 microns to be formed. The heat treatment of step c) is then carried out. Entry into the oven is done at 70°C , the ramp temperature rise ramp is $1^\circ/\text{min}$ until it reaches a plateau at 250°C , for a period of 4 hours. A temperature ramp down to $1^\circ/\text{min}$ is then operated up to 100°C before removing the structure from the oven. The thinned structure 6' then undergoes a second step of thinning the thinned layer 2' to a effective thickness of 10 microns to form the effective layer 20.

The hybrid structure 60 thus obtained is integral and has a consolidated bonding interface 5 whose bonding energy is greater than or equal to 1000 mJ/m , or even greater than 1500 mJ/m^2 ; it also has a useful integral layer 20 with no

degradation related to "buckling" phenomena, despite the presence of non-bonded areas at its interface of a size between 50 and 150 microns. Such a hybrid structure 60 can then be used for the development of acoustic wave devices.

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

CLAIMS

1. A method of manufacturing a hybrid structure (60) having a effective layer (20) of piezoelectric material with a effective thickness disposed on a support substrate (1) that has a support thickness and a coefficient of thermal expansion less than that of the effective layer (20), the method comprises:

a) A step of providing a bonded structure (6) comprising a donor substrate (2) of piezoelectric material and the support substrate (1), the bonded structure (6) having a bonding interface (5) between these two substrates;

b) A first step of thinning the donor substrate (2) to form a thinned layer (2'), having an intermediate thickness, disposed on the support substrate (1); the whole forms a thinned structure (6');

c) A heat treatment step of the thinned structure 6' at an annealing temperature;

d) A second thinning step, after step c), of the thinned layer (2') to form the effective layer (20);

the method being characterized in that it comprises, prior to step b), a step a') of determining a range of intermediate thicknesses avoiding a degradation of the thinned structure (6') during the step c), the range being defined by a threshold thickness and a maximum thickness, and the intermediate thickness of the thinned layer (2') having being chosen in this range; wherein the threshold thickness and the maximum thickness are determined respectively from a first sensitivity model and a second sensitivity model,

wherein the first sensitivity model is associated with a relaxation of the thinned layer in compression on the support substrate and the second sensitivity model is associated with rupture of the support substrate, constrained in extension by the thinned structure during the heat treatment.

2. A method of manufacturing a hybrid structure (60) according to the preceding claim, wherein the first sensitivity model has input parameters including the support thickness, the thermal expansion coefficients of the donor substrate (2) and the

support substrate (1), the annealing temperature and a maximum size of unglued areas found at the bonding interface (5) of the bonded structure (6).

3. A method of manufacturing a hybrid structure (60) according to one of the preceding claims, wherein the second sensitivity model has input parameters including the support thickness, the coefficients of thermal expansion of the donor substrate (2) and the support substrate (1) and the annealing temperature.

4. A method of manufacturing a hybrid structure (60) according to one of the preceding claims, comprising after step a') and prior to step b), a step a'') of recycling the bonded structure (6), when the determining step a') establishes the threshold thickness higher than the maximum thickness or the maximum thickness less than the effective thickness.

5. A method of manufacturing a hybrid structure (60) according to the preceding claim, wherein the step a'') of recycling comprises a detachment at the bonding interface (5) of the bonded structure (6).

6. A method of manufacturing a hybrid structure (60) according to the preceding claim, wherein the step a'') of recycling comprises the reuse of the donor substrate (2) and the support substrate (1) from the detachment for a new stage a) to provide a bonded structure (6).

7. A method of manufacturing a hybrid structure (60) according to one of the preceding claims, wherein the second thinning step d) may further comprise a step of thinning the support substrate (1).

8. A method of manufacturing a hybrid structure (60) according to one of the preceding claims, wherein the effective layer (20) is composed of a material selected from the group:
5 lithium tantalate (LiTaO_3), lithium niobate (LiNbO_3), aluminium nitride (AlN), zinc oxide (ZnO).

9. A method of manufacturing a hybrid structure (60) according to one of the preceding claims, wherein the support substrate (1) is composed of a material selected from the
10 group: silicon, III-V semiconductor, silicon carbide, glass, sapphire.

10. A method of manufacturing a hybrid structure (60) according to the preceding claim, wherein the support substrate (1) comprises one or more surface layers.

15