DESCRIPTION

TITLE: METHOD FOR ASSEMBLING TWO SUBSTRATES BY MOLECULAR ADHESION

FIELD OF THE INVENTION

[0001] The invention relates to a method for assembling two substrates by molecular adhesion. It is particularly useful in the fields of microelectronics, microsystems, photonics, etc.

TECHNOLOGICAL BACKGROUND OF THE INVENTION

[0002] Molecular adhesion is a method for assembling two bodies during which the main faces or surfaces of these two bodies, which are perfectly clean, flat and smooth, are brought into intimate contact with one another to promote the development of molecular bonds, for example of the van der Waals or covalent type. The two bodies are then assembled without the use of adhesives. These bonds can be strengthened by applying a heat treatment.

[0003] This method is used in particular for the manufacture of substrates used in the fields of microelectronics, microsystems, photonics, etc. In these fields, substrates generally take the form of circular wafers of materials that may be monocrystalline, polycrystalline or amorphous, conductive, semiconductive or insulating.

[0004] In these fields, and to facilitate the assembly of the substrates, it is customary to form a surface dielectric layer, typically of silicon oxide, on one and/or the other of these two substrates, by deposition, optionally followed by a polishing step, or by simple oxidation when the substrate is formed from or contains silicon. It is also customary to prepare the main faces to make them clean (notably in terms of particles and contaminants) and smooth (to provide a

surface roughness typically below 0.5 nm root mean square measured by atomic force microscopy over a 5 micron by 5 micron field of view).

[0005] After their preparation, the two substrates are placed one on top of the other, at the level of their main faces. The application of a pressure to one or other of the two substrates brings the main faces into intimate and punctual contact, and propagates this intimate contact across the entire extent of the main faces in the form of a wave, known as a "bonding wave".

[0006] It is also sometimes envisaged to make at least one of these faces reactive by applying a plasma, typically oxygen or nitrogen. This surface preparation is designed to increase the bonding energy between the two assembled substrates. In this regard, it is possible to refer to Paul Lindner's publication "Plasma activated wafer bonding for thin silicon on insulator substrate fabrication." Proceedings of the Electrochemical Society, 2004. Figure 1 shows equipment 1 for applying such a plasma treatment to a substrate 2 for activation thereof prior to bonding. This equipment comprises an activation chamber 3, generally at sub-atmospheric pressure and into which a controlled flow of oxygen or nitrogen is introduced. The chamber contains two electrodes 4a, 4b, between which plasma is formed by ionization of oxygen or nitrogen molecules. This plasma is initiated by applying a radiofrequency power RF (typically 13.56 MHz) to one of the electrodes 4a using a generator G, while the other electrode is grounded 4b. One of the electrodes may correspond to or be included in the susceptor which is substantially sized to support the substrate 2, as shown in Figure 1.

[0007] The radiofrequency power density of the plasma corresponds to the radiofrequency power applied to the electrodes adjusted to (that is, divided by) the facing surface area of the electrodes, this surface area being substantially equal to the exposed surface area of the substrate 2.

[0008] In order to improve the quality of the assembly of two substrates, document WO2023202917A1 proposes to exploit a step of activating the surface dielectric layer which covers the at least one of the substrates to introduce, in this layer, a dose of sulfur greater than 3.0 E13/cm^2.

OBJECT OF THE INVENTION

[0009] One aim of the invention is to improve the approach proposed by this document.

BRIEF DESCRIPTION OF THE INVENTION

[0010] In order to achieve this aim, the object of the invention proposes a method for assembly by molecular adhesion of two substrates each having a main face, the at least one of the two substrates being provided with a surface dielectric layer on the side of its main face.

[0011] According to the invention, the method comprises the following steps:
(a) activating the surface dielectric layer, the activation comprising exposing the surface dielectric layer to a plasma formed between two electrodes of an activation chamber, the plasma exposure being carried out for an activation time of between 15 seconds and 2 minutes during which a radiofrequency power is applied to one of the electrodes and comprising introducing into the activation chamber a controlled flow of oxygen or nitrogen and a controlled flow of a gas comprising sulfur;
(b) bringing the main faces of the two substrates into contact, then;
(c) initiating and propagating a bonding wave between the main faces of the two substrates to assemble them together.

[0012] This method is remarkable in that the radiofrequency power has a density strictly greater than 1.1 W/cm^2.

[0013] According to other advantageous non-limiting features of the invention, taken alone or according to any technically feasible combination:

- the radiofrequency power density is between 1.4 W/cm^2 and 1.7 W/cm^2;
- the activation chamber is placed at a pressure of less than 50 milli-Torr (6.66 Pa), preferentially 30 milli-Torr (4 Pa);
- the controlled flow of oxygen or nitrogen consists of an oxygen flow of 75 sccm;
- the gas comprising sulfur is sulfur hexafluoride;
- the controlled flow of sulfur hexafluoride is formed of a flow of less than 7 sccm, for example 4 sccm;
- the controlled flow of sulfur hexafluoride is introduced into the activation chamber for a specified period of the activation time;
- the specified period lasts less than 10 seconds;
- the specified period is respectively preceded and followed by periods during which only the oxygen or nitrogen flow is introduced into the activation chamber;
- the assembly method comprises a step of depositing the surface dielectric layer on at least one of the two substrates;
- the deposition is performed by a plasma-enhanced chemical vapor deposition technique;
- the surface dielectric layer is less than 90 nm thick;
- the activation step is the only step applied to the surface dielectric layer to reduce the roughness thereof.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] Other features and advantages of the invention will emerge from the following detailed description of the invention with reference to the appended figures, in which:

[Fig. 1]

Figure 1 shows plasma activation equipment suitable for implementing an activation step of a method in accordance with the invention;

[Fig. 2]

Figure 2 shows a graph linking the thickness of a deposited silicon oxide surface layer to its roughness, as measured by X-ray reflectivity, before and after the application of a plasma activation comprising a fluorinated species;

[Fig. 3]

Figure 3 shows graphs illustrating the smoothing effect of the dielectric layer according to the value of certain plasma activation parameters (pressure prevailing in the chamber, radiofrequency power and SF6 flow rate);

[Fig. 4a] [Fig. 4b] [Fig. 4c] [Fig. 4d] [Fig. 4e] [Fig. 4f] [Fig. 4g]

Figures 4a, 4b, 4c, 4d, 4e, 4f and 4g show an application of an assembly method in accordance with the invention to form a composite substrate;

[Fig. 5]

Figure 5 shows a composite substrate that can be formed by applying an assembly method in accordance with the invention.

DETAILED DESCRIPTION OF THE INVENTION

[0015] The applicant has continued the studies reported in document WO2023202917A1 relating to a method for assembly by molecular adhesion of two substrates each having a main face. At least one of the two substrates is provided with a surface dielectric layer on the side of its main face. This method comprises the steps of bringing the main faces of the two substrates into contact, then initiating and propagating a bonding wave between the main faces of the two substrates to assemble them together.

[0016] According to this document, the method comprises, prior to the contacting step, a step of preparing the surface dielectric layer aimed at introducing, into this layer, a dose of sulfur greater than 3.0 E13/cm^2. This preparation step leads to a significant increase in the bonding energy of the two assembled substrates. When the sulfur dose exceeds the above-mentioned dose, the bonding wave propagates at a reduced speed which eliminates, or at least significantly reduces, the peripheral bonding defects

(often referred to as "pimples") that develop at the bonding interface, where the bonding wave meets the edge of the substrates.

[0017] In a particular embodiment, the preparation step comprises activating the surface dielectric layer by a nitrogen or oxygen plasma comprising sulfur hexafluoride (SF6). This activation is carried out over an activation time of between 15 seconds and 2 minutes during which the substrate is exposed to the nitrogen or oxygen plasma. A controlled quantity of sulfur hexafluoride is mixed with the oxygen or with the nitrogen for a specified period of the activation time which is preceded and followed by periods during which the surface dielectric layer is exposed to the oxygen or nitrogen plasma.

[0018] More precisely, under so-called "reference" application conditions, activation of the surface dielectric layer comprises introducing oxygen (O2) into the activation chamber at a flow rate of 75 sccm (standard cubic centimeter per minute) for a duration of 30 seconds. Within this 30-second period, about 11 seconds after the start thereof, a flow rate of 5 sccm of SF6 is introduced for a period of 5 seconds. During this treatment, the activation chamber is maintained at 50 mTorr (6.66 Pa) and 200 W of radiofrequency power is applied to one of the electrodes in the chamber.

[0019] Surprisingly, the applicant observed that the activation of a dielectric layer under these reference conditions had the effect of reducing the roughness of this dielectric layer, whereas this is not the case with the activation of a surface dielectric layer by a plasma consisting solely of oxygen.

[0020] Roughness is usually measured by atomic force microscopy. According to this technique, a nanometer-sized tip carried by a flexible arm is scanned over a measuring field on the surface to be characterized, this field having a dimension of the order of a micrometer to a few micrometers sideways. The surface topography means that the arm is flexed during this scanning. By measuring this flexion, a surface roughness measurement can be established

over the entire measuring field. The measurement has a resolution of less than 1 nm vertically, but of the order of 5 to 10 nm laterally, mainly due to the size of the measuring tip.

[0021] The experiments reported in the above-mentioned document WO2023202917A1 were notably carried out on lithium tantalate wafers on which a 30 nm-thick silicon oxide surface layer had previously been formed by PECVD (Plasma Enhanced Chemical Vapor Deposition). Due to the electrically insulating nature of this wafer, the silicon oxide layer tends to become electrically charged, which makes it difficult to measure roughness by atomic force microscopy, as the measuring tip tends to be electrostatically retained on the surface of the wafer, which disrupts the measurement. Furthermore, a 30 nm-thick deposited layer of silicon oxide generally has a relatively low roughness, below the limit required for wafer bonding by molecular adhesion, so the question of roughness is not addressed by document WO2023202917A1.

Experiments

[0022] To analyze in greater detail the effect of activation on the surface dielectric layer, and in particular on its roughness, the applicant carried out roughness measurements using X-ray reflectivity (referred to as XRR in the relevant scientific literature). The basic principle of this technique consists of projecting an X-ray beam onto the surface to be characterized and of measuring the intensity of the reflected X-rays. The measuring field is typically of the order of mm^2. With the help of a simulation of the reflectivity model, a highly accurate measurement of the thickness of a layer, surface roughness and interface roughness can be obtained. The short wavelength of X-rays, of the order of 0.1 nm, allows atomic resolution to be achieved, although the measurement is in reciprocal space, which is different from the measurements provided in real space by AFM. This measurement is not affected by any electrical charge present in the surface layer.

[0023] XRR roughness measurement observations are plotted on the graph in Figure 2. This shows the measured roughness R of a dielectric layer (on the X-axis in arbitrary units) according to the thickness of this layer T (on the Y-axis in nm). In the reported measurements, this is a layer of silicon dioxide deposited on a silicon substrate by PECVD. Curve A shows the generally linear relationship between the thickness T and the roughness R of the layer immediately after deposition thereof and curve B shows the XRR measurements after the activation step under the reference application conditions described hereinbefore. This graph shows the roughness line C of the as-deposited layer (curve A), above which the surface conditions, even after the smoothing obtained by applying the activation step, do not allow molecular adhesion bonding of sufficient quality to be obtained.

[0024] To make the most of this observation, and in a new series of experiments, the applicant studied the effect of activation equipment parameters, notably the radiofrequency power applied to one of the electrodes and the vacuum level in the chamber, on the roughness of a surface dielectric layer.

[0025] These experiments were carried out on 150 mm diameter silicon wafers on which a 50 nm layer of silicon oxide was deposited by PECVD. Each wafer of a pair of these wafers has undergone an activation step before the wafers of the pair are assembled together, by molecular adhesion. The silicon oxide layers have not undergone any other treatment to reduce their roughness, in particular they have not been treated by polishing. The bonding energy was measured after reinforcement heat treatment at 180°C for 60 minutes, using a "double cantilever beam" method in an anhydrous environment.

[0026] A summary of the results obtained is presented in the table below in which the pressure in the activation chamber, the radiofrequency power applied to one electrode of the plasma equipment and the flow rate of SF6 introduced into the chamber over the 5-second period were varied with respect

to the reference conditions. The table also shows the XRR roughness measured and the average bonding energy measured after a 100°C-1h heat treatment applied to the assembly. For the sake of completeness, it is specified that the frequency of the radiofrequency signal applied to one of the electrodes was 13 MHz.

Ref	Pressure (mT)	Power (W)	SF6 flow rate (sccm)	Pre-activation XRR roughness (in A)	Post-activation XRR roughness (in A)	Anhydrous bonding energy (mJ/m^2)
1	150	100	4	17.3	15.1	
2	90	200	5	18	8.5	
3	30	200	6	17.5	6.2	2780
4	90	150	6	17.6	10.3	
5	30	200	4	17.6	5.9	2785
6	150	200	4	17.2	9.4	2510
7	90	150	6	17.2	9.6	2495
8	30	150	4	17.6	7.6	2735
9	90	150	5	17.8	10.4	2612
10	30	191.5	7	17.7	6.9	2765
11	150	200	7	17.8	9.7	
12	150	200	5	17.9	9.8	2510
13	50	150	5	17.7	9.1	2675
14	30	300	4	17.7	4.6	2835

[0027] These data are summarized on the graphs in Figure 3 which model the effect of varying a parameter (pressure Pr, power Pa or SF6 flow rate Db) on the smoothing of the dielectric layer (variation in roughness ΔR before/after activation).

[0028] Figure 3 shows that the smoothing effect is highly sensitive to the radiofrequency power of the plasma, with the smoothing effect being maximized in the window studied for the maximum explored power of 300 W. It is therefore generally desirable for activation to be carried out at a relatively high power level, strictly greater than 200 W (i.e., a power density strictly greater than 1.1 W/cm^2 adjusting the power to the surface area of the wafer),

and preferably between 250 W and 300 W (a power density of between 1.4 W/cm^2 and 1.7 W/cm^2).

[0029] The smoothing effect is also sensitive, to a lesser extent, to the pressure prevailing in the chamber, a relatively low pressure leading to a greater smoothing effect. Also, and advantageously, this pressure is selected to be placed at a pressure less than 50 milli-Torr (6.66 Pa), preferentially less than 30 milli-Torr (4 Pa).

[0030] Finally, the smoothing effect appears to be very insensitive to the SF6 flow rate, which can therefore be selected freely, for example at a relatively low flow rate of 4 sccm.

[0031] We note that the bonding energy for all the bonds analyzed is particularly high, in line with the teachings of document WO2023202917A1. This is particularly true of the bonding of the wafers on line 14 of the table, which were activated with the highest power of 300 W.

Assembly method

[0032] It is possible to benefit from the results just presented in a sequence formed of the previously described steps of contacting the main faces of the two substrates, and initiating and propagating a bonding wave. To do this, prior to the contacting step, a step is provided of activating the surface dielectric layer comprising exposing this layer to a plasma formed between two electrodes in an activation chamber. The surface dielectric layer may have been formed on the substrate by deposition, for example by PECVD. The thickness can be selected relatively freely, for example less than 90 nm or between 30 nm and 90 nm, as the surface roughness which can be relatively high for thicker deposits will be rectified by the activation step, due to its smoothing effect.

[0033] The pressure prevailing in the activation chamber can be controlled to be less than 50 milli-Torr (6.66 Pa), preferentially less than 30 milli-Torr (4 Pa). A controlled flow of oxygen or nitrogen and a controlled flow of a gas comprising sulfur are introduced into the chamber. This controlled flow of oxygen or nitrogen may be equal to, or of the order of, 75 sccm. The controlled flow of the gas comprising sulfur can be between 3 sccm and 7 sccm of SF6.

[0034] Exposure is carried out for an activation time of between 15 seconds and 2 minutes, during which a radiofrequency power strictly greater than 200 W is applied to one of the electrodes. Preferably the radiofrequency power is between 250 W and 300 W.

[0035] The gas comprising sulfur, for example SF6, can be introduced at a controlled flow rate for all of this time, or for part of this time only, to mix with oxygen or with nitrogen for a specified period of the activation time. Preferably, this specified period does not include the moment of plasma ignition, as this ignition can lead to the introduction of sulfur species of the plasma into the surface layer in an unrepeatable manner, which can be detrimental to the good command of the method. Advantageously therefore, the specified period during which the surface dielectric layer is exposed to the plasma formed by a sulfur-containing gas is respectively preceded and followed by periods during which the surface dielectric layer is exposed to the plasma formed solely by an activating gas of oxygen or nitrogen.

[0036] The step of activating the surface dielectric layer is followed by the step of bringing the main faces of the two substrates into contact, then by the step of initiating and propagating a bonding wave between the main faces of the two substrates to assemble them together.

[0037] Between the activation step and the contacting step, a step of cleaning the main face of the substrate can be provided. This cleaning step may correspond to or comprise brushing this face while pouring in a liquid, such as

demineralized water or an SC1 (acronym for "standard clean 1") solution. Advantageously, the cleaning step is applied to the main faces of both substrates, directly prior to their assembly.

Exemplary application

[0038] The assembly method described above has a wide range of applications. It can notably be used in a double transfer method of a layer, a detailed description of which can be found in document EP703609 or document WO0237556A1. As detailed in these documents, such a double transfer makes it possible to bypass the problem associated with the differential expansion that arises during the direct transfer of a layer, taken from a so-called donor substrate, onto a final support, when this donor substrate and the final support have different coefficients of thermal expansion. In very general terms, this double transfer method involves first transferring the thin layer onto an intermediate support having a coefficient of thermal expansion equal to or close to that of the thin layer. The thin layer is assembled to the intermediate support at a first adhesion interface, by molecular bonding, having a first adhesion energy. The free face of the thin layer is then assembled to the final support at a second adhesion interface, also by molecular bonding, this second interface having a second adhesion energy greater than the first. In a subsequent step, the final support and/or the intermediate support, between which the thin layer is sandwiched, are mechanically stressed in order to dismantle the intermediate support from the thin layer at the first interface which has the lowest adhesion energy, and thus complete the transfer of the thin layer to the final support.

[0039] By way of illustration, we wish to form a composite structure S, shown in Figure 5, to form radiofrequency components, the composite structure S being formed by a thin piezoelectric layer 7, for example made of lithium tantalate, on a final support 11 made of silicon. Silicon has an estimated coefficient of thermal expansion of 2.6 $x10^{-6}\,K^{-1}$. Lithium tantalate is

anisotropic and has a coefficient of thermal expansion of 16.0 $x10^{-6}$ K^{-1} along axis a11 and 4.0 $x10^{-6}$ K^{-1} along axis a33. Regardless of the crystallographic axis considered, these two materials have very different coefficients of thermal expansion, which makes the realization of this structure using a "direct" approach problematic.

[0040] To avoid any ambiguity, the expression “coefficient of thermal expansion” used in this description in relation to a layer or to a substrate refers to the expansion coefficient along a direction defined in the main plane defining this layer or this substrate. If the material is anisotropic, the value of the coefficient used will be the value with the greatest amplitude. The value of the coefficient is that which is measured at room temperature. When we indicate that these coefficients are "different", we mean that their difference exceeds 10% of the smallest coefficient. Conversely, when we indicate that these coefficients are identical, we mean that their difference is less than or equal to 10% of the smallest coefficient.

[0041] In this radiofrequency application in which the thin layer 7 is made of piezoelectric material, the final support 11 can advantageously comprise a base substrate 11a made of monocrystalline silicon, which can have a high resistivity, greater than 1000 ohm.com. The base substrate 11a can be provided with an electric charge trapping layer 11b, for example a polycrystalline silicon layer. In this case, the trapping layer 11b is arranged in the composite substrate S between the piezoelectric thin layer 7 and the base substrate 11a. The composite substrate can also comprise a buried dielectric layer 12 arranged between the piezoelectric thin layer 7 and the final support 11, in contact between this thin layer 7 and the charge trapping layer 11b when this layer is present. Advantageously, the buried dielectric layer 12 is made of silicon oxide or silicon oxynitride. This latter material notably forms a diffusion barrier for certain species contained in the thin layer 7 towards the charge trapping layer 11b (hydrogen or lithium, for example), which can degrade its electrical trapping qualities.

[0042] To manufacture such a composite substrate S, a method is used to transfer the thin layer 7 onto the final support 11, by means of a double transfer of this layer, which takes advantage of the assembly method by molecular adhesion discussed in the first section of this description.

[0043] More precisely, and with reference to Figures 4a to 4g, an intermediate structure Si is first formed comprising the thin layer 7 assembled to an intermediate support 5 at a first adhesion interface IA1. The thin layer 7 and the intermediate support 5 have identical coefficients of thermal expansion. For example, the thin layer can be removed from a lithium tantalate donor substrate and transferred onto an intermediate support 5 consisting of a lithium tantalate bulk substrate.

[0044] The transfer can be implemented via Smart Cut™ technology, as is shown in Figures 4a to 4c. This technology, well known to those skilled in the art, proposes to transfer the thin layer by assembling the donor substrate 6 and the intermediate support 5. A dielectric layer 8, typically a silicon oxide, is first formed on the donor substrate 6 and/or on the intermediate support 5 and is sandwiched, in the intermediate structure Si, between the transferred thin layer 7 and the support 5. The thin layer is defined in the donor substrate by the introduction of light species, usually by implantation of hydrogen and/or helium ions, these species tending to form a fragile zone 9 delimiting the thin layer. The thin layer 7 is detached from the rest of the donor substrate 6, and transferred to the support, by mechanically or thermally stressing the assembly formed of the donor substrate and the support (Figure 4c), which causes the donor substrate to fracture at the fragile zone 9.

[0045] As an alternative to using Smart Cut technology, the donor substrate can be thinned mechanically and/or chemically, after its assembly with the intermediate support, to define the thin layer. In this approach, a dielectric

layer is also applied to the donor substrate and/or to the intermediate support to facilitate assembly.

[0046] Whether the thin layer is formed by detachment at a fragile zone of the donor substrate or by thinning of this donor substrate, its transfer requires the donor substrate 6 to be made integral with the intermediate support 5 at a first adhesion interface A1 having sufficient energy. To that effect, at least one of the faces of the donor substrate 6 and of the intermediate support 5, which are intended to be assembled together, can be plasma-activated. It is also possible to provide for a moderate annealing of the intermediate structure Si, before the thin layer 7 is detached, in order to boost the adhesion energy and allow the transfer of the thin layer.

[0047] It is noted that, since the donor substrate 6 from which the thin layer 7 is taken and the intermediate support have the same coefficients of thermal expansion, this step of preparing the intermediate support 5 can comprise heat treatment steps without generating stresses likely to damage it. In the case of a donor substrate and a lithium tantalate intermediate support, the assembly formed by the donor substrate 6 and the intermediate support 7 can be raised to a temperature of 200°C to 300°C, sufficient to cause the fracture of the donor substrate and the transfer of the thin layer 7 as part of a transfer implemented according to Smart Cut technology. This temperature is greater than that which would have been applied to an assembly formed of the donor substrate 5 and of the final silicon substrate 11, due to the large difference in the coefficient of thermal expansion.

[0048] At the end of the step of transferring the thin layer 7 (Figure 4c), a finishing step can be applied, particularly when the thin layer 7 has been transferred according to Smart Cut technology, to restore the crystallographic and surface quality of the thin layer 7. This may involve annealing this layer in a neutral or oxidizing atmosphere and/or thinning it, for example by chemical-mechanical polishing or ion etching.

[0049] Continuing the description of the transfer method which is the subject of this part of the description, it then provides (Figure 4d) for the formation of a surface dielectric layer 10 on the exposed face of the thin layer 7 of the intermediate structure Si. This surface dielectric layer 10 is intended to form, at least in part, the buried dielectric layer 12 of the composite substrate S. It also allows the activation and molecular adhesion step presented in the previous section of the description to be deployed. This surface dielectric layer 10 can also be made of silicon oxide or silicon oxynitride. It is advantageously deposited, for example according to a PECVD deposition technique. It can have any thickness, preferentially between 10 nm and 50 nm, and even more preferentially between, strictly, 30 nm and 90 nm. In such a range, the surface dielectric layer has a sufficient thickness to compensate for any thinning that may occur during the subsequent activation step and does not exhibit excessive roughness, which could not be sufficiently reduced during this activation step.

[0050] Preferentially, and when the surface dielectric layer 10 is selected within the aforementioned thickness range, the transfer method is devoid of any treatment, other than the activation step, to reduce the roughness thereof. It is in this case notably devoid of any chemical-mechanical polishing aimed at reducing the roughness of the surface dielectric layer 11, which is highly advantageous.

[0051] In a subsequent step shown in Figure 4e, the surface dielectric layer 10 is activated by exposure to a plasma formed between two electrodes subjected to a radiofrequency power density strictly greater than 1.1 W/cm^2 of an activation chamber into which a controlled flow of a gas comprising sulfur is introduced. The frequency of the radiofrequency signal can be selected at 13 MHz or of the order of 13 MHz, to within 25%. As mentioned in the previous section of this description, such activation allows the surface to be prepared, notably by reducing roughness, and produces particularly high adhesion energy during the subsequent molecular adhesion step.

[0052] All the variants described in the first section of this description can be implemented in the present application. Plasma exposure can notably be carried out for an activation time of between 15 seconds and 2 minutes during which a controlled flow of oxygen or nitrogen is introduced into the activation chamber in addition to the gas comprising sulfur. The controlled flow of a gas comprising sulfur, which may be sulfur hexafluoride, is introduced into the activation chamber for a specific period of the activation time, for example a duration less than 10 s. This period can be placed in the middle of the activation time, and be preceded and followed by periods during which only the oxygen or nitrogen flow is introduced into the activation chamber. The vacuum level present in the activation chamber during the activation period can also be controlled, for example to set it at a pressure of less than 50 milli-Torr (6.66 Pa), preferentially at 30 milli-Torr (4 Pa).

[0053] Regardless of the precise conditions under which the step of activating the surface dielectric layer 10 is carried out, this is followed by the assembly of the thin layer 7, via the surface dielectric layer 10, to the final support 11 (Figure 4f). A second adhesion interface IA2 of the thin layer 7 is thus defined, this second adhesion interface IA2 having, due to the activation step of the surface dielectric layer 10, a higher adhesion energy than that of the first interface IA1 which holds the thin layer 7 to the intermediate support 5.

[0054] In the illustrated example, the final support 11 is composed of a monocrystalline silicon base substrate 11a provided with an electric charge trapping layer 11b. This trapping layer 11b may itself have been previously provided with a dielectric layer, for example by oxidation or by deposition. This dielectric layer, when it is present, combines with the surface dielectric layer 10 formed on the thin layer 7 to constitute the buried dielectric layer 12 of the composite substrate S.

[0055] This assembly uses a molecular adhesion technique, that is, bringing the final support 11 into contact with the surface dielectric layer 10, then initiating and propagating a bonding wave between the main faces brought into contact to assemble them together.

[0056] The final support 11 can be plasma-activated prior to its assembly by molecular adhesion to the surface dielectric layer 10. This plasma activation may be identical to that applied to the surface dielectric layer 10 or different. For example, this may involve exposing this final support 11 to a plasma consisting of oxygen or nitrogen, without introducing a controlled quantity of a gas comprising sulfur into the activation chamber.

[0057] In any case, at the end of this assembly step shown in Figure 4f, the thin layer 7 is sandwiched between, on the one hand, the intermediate support 5, at a first adhesion interface IA1, and, on the other hand, the final support 11, at a second adhesion interface IA2. Due to the particular activation step of the surface layer, the adhesion energy of the second interface is greater than that of the first interface.

[0058] To enhance the adhesion energy of the second interface IA2, in this example, the structure comprising the temporary support and the final support can be exposed to a temperature not exceeding 100°C.

[0059] A final step of the transfer method, shown in Figure 4g, aims to dismantle the intermediate support of the sandwich structure in which the thin layer is arranged and thus complete the transfer of the thin layer 7 to the final support 11. This is achieved by mechanically stressing the final support and/or the intermediate support. This mechanical stress tends to break the adhesion interface having the lowest energy, that is the first interface IA1 to release the thin layer 7 from the intermediate support 5.

[0060] The mechanical stressing step may comprise inserting a blade, or more generally a tool, between the intermediate support 5 and the final support 11, and applying a force by the blade or by the tool to separate the two supports 5, 11.

[0061] The dielectric layer 8, or residues of this layer, which may cover the thin layer 7, can then be removed to finalize preparation of the composite substrate S as shown in Figure 5.

[0062] Naturally, the invention is not limited to the embodiments described, and it is possible to add alternative embodiments without departing from the scope of the invention as defined by the claims.

[0063] Thus, the application just described is by no means limited to a lithium tantalate thin layer 7. More generally, it applies to a thin layer 7 consisting of any material. When this material is selected to exhibit piezoelectric properties as is the case in the example described, it may also be lithium niobate.

[0064] Although sulfur hexafluoride is used herein as an example of a gas comprising sulfur (and fluorine), the invention is by no means limited to the use of this gas. In particular, any sulfur-containing gas such as sulfuryl fluoride (SO_2F_2) or thionyl tetrafluoride (SO_2F_4) can be used as a replacement.

[0065] The activation step according to the invention can be applied to a single surface dielectric layer formed on one of the two substrates to be assembled, even if both substrates comprise such a surface dielectric layer. The activation step can also be applied to each of the substrates, and in this case each is provided with a surface dielectric layer.

This surface dielectric layer can be formed of SiO_2 as shown in the present description. More generally, however, it can be a dielectric layer of any kind, for example SiON, or silicon nitride.

Claims

1. A method for assembly by molecular adhesion of two substrates each having a main face, at least one of the two substrates being provided with a surface dielectric layer on its main face, the method comprising the following steps:

(a) activating the surface dielectric layer, the activation comprising exposing the surface dielectric layer to a plasma formed between two electrodes (4a, 4b) of an activation chamber (3), the plasma exposure being carried out for an activation time of between 15 seconds and 2 minutes during which a radiofrequency power is applied to one of the electrodes and comprising introducing into the activation chamber (3) a controlled flow of oxygen or nitrogen and a controlled flow of a gas comprising sulfur;

(b) bringing the main faces of the two substrates into contact, then;

(c) initiating and propagating a bonding wave between the main faces of the two substrates to assemble them together;

the method being characterized in that the radiofrequency power has a density strictly greater than 1.1 W/cm^2.

2. The assembly method according to the preceding claim wherein the radiofrequency power density is between 1.4 W/cm^2 and 1.7 W/cm^2.

3. The assembly method according to the preceding claim wherein the activation chamber (3) is placed at a pressure of less than 50 milli-Torr (6.66 Pa), preferentially 30 milli-Torr (4 Pa).

4. The assembly method according to one of the preceding claims wherein the controlled flow of oxygen or nitrogen is formed of an oxygen flow of 75 sccm.

5. The assembly method according to one of the preceding claims wherein the gas comprising sulfur is sulfur hexafluoride.

6. The assembly method according to the preceding claim wherein the controlled flow of sulfur hexafluoride is formed of a flow of less than 7 sccm, for example 4 sccm.

7. The assembly method according to one of the preceding claims wherein the controlled flow of sulfur hexafluoride is introduced into the activation chamber (3) for a specified period of the activation time.

8. The assembly method according to the preceding claim wherein the specified period lasts less than 10 seconds.

9. The assembly method according to one of the two preceding claims wherein the specified period is respectively preceded and followed by periods during which only the oxygen or nitrogen flow is introduced into the activation chamber.

10. The assembly method according to one of the preceding claims comprising a step of depositing the surface dielectric layer on at least one of the two substrates.

11. The assembly method according to the preceding claim wherein the deposition is performed by a plasma-enhanced chemical vapor deposition technique.

12. The assembly method according to one of the two preceding claims wherein the surface dielectric layer has a thickness less than 90 nm.

13. The assembly method according to one of the preceding claims wherein the activation step is the only step applied to the surface dielectric layer to reduce the roughness thereof.