METHOD FOR REDUCING ROUGHNESS OF A THICK INSULATOR LAYER

This invention relates to a method for manufacturing substrates intended for use in the electronics, optoelectronics and optics fields, including a step to smooth a thick insulator layer, in other words to reduce its roughness.

The invention also relates to a manufacturing method that includes the above mentioned smoothing method and bonding and layer transfer steps.

The invention is used in a particular application for making composite "SOI" and "sSOI" type substrates.

As a reminder, substrates known as "SOI" (Silicon On Insulator) substrates correspond to substrates in which an insulator layer, more precisely silicon dioxide (SiO_2) is inserted between a support silicon layer and a superficial silicon layer. In "sSOI" substrates, the superficial silicon layer is strained (strained Silicon On Insulator).

The method for obtaining this type of substrate comprises a step to bond a so-called "support" or

"receiving" substrate on the insulator layer, and a layer transfer step.

In this description, "bonding" should be understood as molecular bonding in which two perfectly plane surfaces bond to each other without application of glue, which is possible at ambient temperature.

The bonding quality obtained is characterized particularly by the bonding energy that is defined as the bond force existing between two layers bonded together.

This quality may be improved by applying an appropriate treatment to the surfaces to be bonded.

The insulation used in the above mentioned composite substrates are particularly oxides, nitrides or oxinitrides.

The state of the art used to obtain these various insulators includes a technique to deposit a layer of silicon dioxide known to the man skilled in the art as "TEOS LPCVD" ("Tetraethylorthosilicate" "Low Pressure Chemical Vapour Deposition").

This technique consists of depositing a film of silicon dioxide, using tetraethylorthosilicate as a source material, and a low pressure vapour phase deposition technique known to the man skilled in the art as LPCVD.

This method has many advantages concerning uniformity and density of the oxide layer obtained, and in particular avoids consuming the substrate layer on which the silicon oxide thus formed is supported, which is not the case during formation of an oxide by a thermal oxidation method.

However, the roughness of silicon dioxide layers deposited using the "TEOS LPCVD" technique is much higher

than the roughness of thermally oxidised layers. For guidance, the surface roughness of a 150 nm thick TEOS oxide is more than 5 Å RMS over a scan width of 1 µm by 1 µm, while the roughness of a thermal oxide is close to about 1.50 Å RMS over the same scan width.

Other deposition techniques are also known, for example such as deposition by LPCVD using silane (SiH_4) as precursor, and Plasma Enhanced Chemical Vapour Deposition (PECVD). Further information on this subject is given in the article by Wolf and Tauber, "Chemical Vapour deposition of amorphous and polycrystalline films", Silicon processing for the VLSI ERA, vol 1, pp 189-207, Process Technology.

However, these deposition techniques lead to an insulator layer with the very high roughness.

Furthermore, the roughness increases with the thickness of the deposited layer.

Consequently, a thick insulator layer (for example oxide), in other words more than 20 nm thick (which is frequently the case when manufacturing SOI type products) is usually made with a roughness that is incompatible with constraints imposed by very good quality molecular bonding. In this case, it is preferable that the roughness should be less than 5 Å RMS to enable bonding, or even less than 2 Å RMS over scan widths of 1 µm by 1 µm, in the context of a layer transfer application known under the commercial name "Smart Cut®".

The state of the art already includes the possibility of submitting a substrate to a plasma treatment.

The "plasma treatment" of a surface to be bonded is defined as exposure of this surface to a gas plasma that

can be done particularly under a vacuum or at atmospheric pressure (prior to bringing the surfaces to be bonded into contact).

This treatment is done by controlling various exposure parameters such as the nature and flow or pressure of the gas supplying the chamber inside which the operation is done, and the power density.

The effect is to modify the structure of the superficial layer of the substrate thus treated.

A distinction is made between two types of treatment, the first hereinafter called "activation plasma" is supposed to improve the bonding energy between two layers and the second hereinafter called "smoothing plasma" that is intended to reduce the surface roughness of the layer thus treated.

Plasma application parameters, and particularly energy, may be different in the two cases.

The article by D.M. Hansen et al. entitled "Chemical role of oxygen plasma in water bonding using borosilicate glasses" Applied Physics Letters, Volume 79, number 21, 19 November 2001, describes a method of activation plasma of a thin layer of borosilates, deposited by LPCVD.

Borosilicate type glasses are boron trioxide (B_2O_3) and silicon dioxide (SiO_2) alloys.

The experiment described in this article relates to the treatment of an approximately 30 Angstrom thick (3 nm) borosilicates layer by an oxygen plasma in RIE (Reactive Ion Etching) mode for five minutes at 0.6 W/cm^2, with a pressure inside the chamber of 30 mTorr (1 mTorr = 1.33 x 10^{-1} Pa).

The results obtained reveal improved bond and show that the roughness of the treated surface is not affected by this activation plasma treatment.

In the article entitled "Surface energy as a function of self-bias voltage in oxygen plasma wafer bonding", Sensors and Actuators 82 (2000) 239-244, D. Pasquariello et al., studied the influence of kinetic energy of ions of an oxygen plasma on the bonding energy of silicon wafers thus treated.

Tests showed that a silicon wafer with an initial roughness of 0.9 Å RMS can have a roughness of about 0.60 Å RMS for a scan width of 1 µm x 1 µm.

The author also concludes that the kinetic energy of plasma ions does not have any influence whatsoever on the smoothing quality of the substrates thus treated.

Furthermore, the article by Moriceau et al. "*Interest of a short plasma treatment to achieve high quality Si-SiO_2-Si bonded structures*", Abstract No. 1006, ECS 2003, showed the smoothing effect of a plasma on thermal oxides of SiO_2. However, this article only concerns oxides with a fairly low initial roughness (2.3 Å RMS for a 0.5 µm x 0.5 µm to 20 µm x 20 µm scan). This article does not mention the possibility of forming an embrittlement zone by a Smart Cut ® type implantation in the substrate supporting the oxide, and consequently nor does it mention the potential beneficial effects of the smoothing plasma observed during a subsequent layer transfer.

Finally, document US-2004/0124416 describes a method of reducing the roughness of a layer of dielectric material that uses a plasma treatment.

However, this document does not mention the possibility of a Smart Cut ® type of treatment for implantation of atomic species between a smoothing plasma treatment and bonding followed by a layer transfer. The beneficial effects on the reduction of the number of the defects observed on the transferred layer are absolutely not envisaged.

On the contrary, the purpose of the invention is to significantly reduce the roughness of a thick insulator layer that is not required or that cannot be formed by oxidation on its first substrate and for which the initial roughness is high.

For the purposes of this description, a "rough" layer means a layer with a roughness greater than or equal to 3 Angstroms RMS, preferably between 3 and 20 Angstroms RMS approximately, for a 2 µm x 2µm scan.

Another purpose of the invention is to provide a method of manufacturing an intermediate substrate that includes an embrittlement zone obtained by implantation of atomic species and that is covered by a thick insulator layer for which the roughness is high, this intermediate substrate possibly being used later in a bonding and layer transfer method, so as to obtain a substrate in which the transferred layer contains few or no defects.

To achieve this, the invention relates to a method of manufacturing a substrate that can be used in the electronics, optoelectronics and optics fields, characterized in that it comprises at least the following steps, performed in this order:

a) deposit an insulator layer with a thickness greater than or equal to 20 nm, with a roughness greater

than or equal to 3 Angstroms RMS, for a scan width of 2 µm x 2 µm on a first so-called "donor" substrate,.

b) the smoothing treatment of the free surface of this insulator layer using a gas plasma formed in a chamber inside which the gas pressure is more than 0.25 Pa, this plasma being created using a radiofrequency generator operating under a power such that it can apply a power density greater than 0.6 W/cm^2 to said insulator layer, the duration of this smoothing treatment being at least 10 seconds.

c) formation of an embrittlement zone by implantation of atomic species inside said donor substrate, to delimit a so-called "active" layer and a remainder.

According to other advantageous and non-limitative characteristics of the invention taken alone or in combination:

- the method includes the following steps carried out after step c):

d) molecular bonding of a second substrate called the "receiver" on said free surface of the insulator layer,

e) withdrawal of said remainder.

- the method comprises a densification annealing step for the insulation deposited in step a), this annealing being done at a temperature of between 700 and 1000°C for a duration of several minutes to several hours in an oxidising or neutral atmosphere.

- said densification annealing treatment is done after the smoothing plasma step b) and before the atomic species implantation step c).

- the smoothing plasma treatment is done with a power density of between 0.6 and 10 W/cm^2, a gas pressure inside the chamber of between 0.25 and 30 Pa and a treatment duration of between 10 and 200 seconds.

- the gas pressure inside the chamber is between 3 and 13 Pa, preferably approximately 7 Pa.

- the duration of the smoothing plasma treatment step b) is between about 30 and 120 seconds.

- the gas used for formation of the smoothing plasma is chosen from among oxygen (O_2), argon (Ar), nitrogen (N_2) or a mixture of these gases.

- the gas used for formation of the smoothing plasma (SP) is chosen such that the nature of the atoms from which it is made is the same as at least one of the atoms forming said insulator layer (2) to be treated.

- between steps c) and d), a activation plasma treatment of said insulator layer is performed using a gas plasma formed in a chamber inside which there is a gas pressure of about 7 Pa, this plasma being created using a radiofrequency RF generator that operates at a power such that it applies a power density exceeding 0.2 W/cm^2 to said insulator layer, the duration of this smoothing treatment being at least 5 seconds.

- the activation plasma treatment is carried out with a power density of between 0.2 and 3 W/cm^2, and a treatment duration of between 5 and 60 seconds.

- the thickness of the insulator layer is greater than or equal to 200 nm.

- the insulation is obtained by a low pressure vapour phase chemical deposition LPCVD technique.

- the insulation is an oxide.

- the oxide is a silicon dioxide obtained by a low pressure chemical vapour phase deposition technique starting from tetraethylorthosilicate (TEOS LPCVD).

- the silicon dioxide (SiO_2) is deposited at a pressure of between 40 and 200 Pa.

- the insulation is a nitride or an oxinitride.

- said active layer comprises silicon.

- said active layer comprises strained silicon.

Other characteristics and advantages of the invention will become clear after reading the description that will be given below with reference to the appended drawings, which represent one possible embodiment as guidance but that is in no way limitative.

On these drawings:

- figures 1A to 1F are diagrams illustrating the different successive steps of a first embodiment of the method according to the invention;

- figures 2A to 2H are diagrams illustrating the different steps of a second embodiment of the method according to the invention;

- figure 3 is a graph representing the edge roughness R of a layer of silicon dioxide after the plasma treatment according to the invention as a function of the applied power, for different application times;

- figure 4 is a graph representing the edge roughness R of a layer of silicon dioxide after the plasma treatment according to the invention as a function of time and for different plasma power ranges;

- figures 5 and 6 are graphs similar to those in figures 3 and 4 respectively, for measurements made at the centre of the silicon dioxide layer;

- figure 7 is a graph showing the number N of different types of defects before and after the smoothing plasma treatment according to the invention;

- figures 8 and 9 are graphs representing the duration t of a bonding wave, expressed in seconds, as a function of the number NO of bonding waves in this bonding time, for the insulator layers (SiO_2) that were and were not affected by the smoothing plasma treatment, respectively and

- figure 10 is a graph representing the number of different types of defects observed on substrates obtained either after completion of the method according to the invention, or after a comparative method.

With reference to figure 1, the figure shows the different steps of a first embodiment of the method according to the invention.

Figure 1A and 1B show a donor substrate 1 before and after it is covered by the deposition of a thick insulator layer 2, respectively. The face of the donor substrate 1 opposite to that on which the insulator layer 2 has been deposited is said to be the "back face" and is marked as reference 13.

The donor substrate 1 may be a single layer or multi layer. It is usually made from a semiconducting material, for example silicon.

The donor substrate 1 may also comprise a strained material such as strained silicon. In the latter case, the substrate is usually multi layer and the strained material layer is then obtained by epitaxy on a layer of support material.

For example, the insulation 2 may be a nitride or oxinitride layer, or preferably an oxide layer.

The insulation layer is greater than or equal to 20 nm thick, preferably 200 nm or more. Its roughness is greater than or equal to 3 Angstroms RMS, for a scan width of 2 µm x 2 µm.

According to the invention, the next step is a smoothing plasma step for which the methods used will be described later. This is shown on figure 1C. The reference SP corresponds to the term "smoothing plasma".

Finally, an atomic species implantation step is carried out as shown in figure 1D.

This implantation provides the means of forming an embrittlement zone 10 inside the donor substrate 1, which delimits an upper thin layer 11 from the remainder 12 of the substrate.

The expression "thin layer" refers to a layer of a few tens or a few hundreds nanometers thick.

Refer to the book "Silicon on Insulator Technologies"; Materials to VLSI, 2nd Edition (Jean-Pierre Colinge) or literature concerning the "Smart Cut" type (registered trademark) method, for a general description of these implantation methods.

According to the invention, the three steps that have just been described, namely the insulation deposit, the smoothing plasma SP treatment and the implantation of atomic species shown on figures 1B, 1C and 1D respectively, are necessarily carried out in this order. However, as will be described later, complementary steps may be inserted between these three steps.

At the end of the implantation step, a substrate 4 called the "intermediate substrate" is obtained that can be used in bonding and layer transfer methods that can be used in electronics, optoelectronics and optics fields.

These steps are illustrated on figures 1E and 1F.

As illustrated on figure 1E, the method can be continued by bonding a receiver substrate 3, on the free surface 20 of the insulator layer 2 of the intermediate substrate 4.

The receiver substrate 3 is made of a semiconductor material.

The next step is detachment of the remainder 12 of the donor substrate 1, along the embrittlement zone 10.

Thus the final composite substrate 5 represented on figure 1F is obtained, in which the insulator layer 2 is inserted inside two layers of semiconducting material 3, 11.

Although it is not shown on the figures, the receiver substrate 3 may be multi layer.

Figure 2 illustrates a variant embodiment of the previous process. Identical elements are marked with the same numeric references.

This variant embodiment is distinguished from the previous embodiment in that it includes two additional steps, one densification heat treatment shown on figure 2D, and the other a activation plasma treatment illustrated on figure 2F.

The other steps in the process are identical to what was described above for figure 1 and have the same numeric references.

The densification annealing step of the insulation 2 that was deposited on the substrate 1 is optional but is recommended.

This densification annealing step is carried out before the atomic species implantation step.

It is also preferably done after the smoothing plasma (SP) step. However, and although this is not shown on the figures, it could also be done after the insulation deposit but before the smoothing plasma step.

The activation plasma (AP) treatment is optional. It may be done on the face on which the smoothing plasma (SP) treatment was done, in other words on face 20 as shown on figure 2F. It could also be done on the face 30 of the substrate 3 that will be bonded onto the face 20. It can also be done on the two faces 20 and 30.

The reference AP stands for activation plasma that denotes a activation plasma treatment.

Finally, although it is not shown on the figures, a pre and/or post-activation plasma (AP) cleaning treatment may be done following the methods described later, after implantation of atomic species and before activation plasma or after activation plasma and before bonding of the receiver substrate 3.

We will now describe the methods of implementing the different steps mentioned above, in further detail.

Methods of depositing the insulator layer:

The insulator layer 2 is formed on the donor substrate 1 by deposition, particularly by vapour phase chemical deposition, and preferably at low pressure, known as LPCVD.

Another technique can also be used, such as plasma enhanced chemical vapour phase deposition, known as PECVD. Further information on this subject is given in the above mentioned article by Wolff and Tauber.

This step of the method may be carried out with a reactor for chemical vapour phase deposition. This

includes a treatment chamber inside which the substrate is contained. The different chemical reagents are then introduced inside this chamber in the form of gas flows at high temperature and low pressure, so as to form an insulator layer 2 after chemical reaction between the different gaseous constituents.

One of the applications aimed at in the invention consists of making an SOI type substrate.

In this case, a preferred variant embodiment of silicon dioxide (SiO_2) consists of making a deposit known under the above mentioned term TEOS LPCVD using tetraethylorthosilicate (TEOS) according to the following chemical reaction:

$Si(OC_2H_5)_4(gas) -> SiO_2(Solid) + 2C_2H_4(gaseous) + 2CH_3CH_2OH(gaseous)$

The pressure inside the LPCVD reactor chamber is between 300 mTorr and 1.5 Torr (namely between 40 and 200 Pa) and preferably close to 750 mTorr, (namely close to 100 Pa).

The thickness of silicon dioxide is adjusted to be at least 20 nm, namely greater than or equal to 200 nm and up to a few micrometers.

Densification annealing:

This is done by a heat treatment at a temperature of between 700 and 1000°C for a duration of several minutes to several hours in an oxidising or neutral atmosphere.

Its purpose is to make the insulation denser and to eliminate carbonaceous species.

Configuration of unit for carrying out smoothing treatment or activation plasma treatment:

The treatment is carried out with a unit comprising a plasma chamber inside which the pressure and composition of the gaseous atmosphere are controlled. Several types of those units exist.

The invention may thus be implemented with a "reactive ion etching" unit known by its abbreviation, "RIE". The unit comprises a single RF (radiofrequency) generator supplying, via a capacitative coupling, an electrode located inside the chamber which supports the substrate 1 covered with the insulator layer 2 to be activated and/or smoothed.

This single RF generator can generate the plasma (i.e. excite its species).

The term "power" as used in the text, which is one of the activation parameters, corresponds more precisely to the power of the generator.

Controlling the power of this generator can both excite the plasma and control the kinetic energy of the ions of the plasma which bombard the surface of the insulator layer 2 to be activated.

The plasma chamber also comprises a second electrode which is not connected to the substrate to be activated. This second electrode is earthed.

In a further variation, it is also possible to implement the invention with a similar unit to that which was mentioned above, but in which the second electrode is connected to a second RF generator.

In this case, the second RF generator (connected to the electrode with which the insulator layer to be treated is not in contact) generates and maintains the plasma. This second generator is then programmed to control the density of the plasma. Controlling the

power of the first generator can only regulate the kinetic energy of the ions of the plasma, which bombard the surface of the layer to be treated.

Smoothing plasma parameters:

The RF power of the plasma is high. It is from 200 W to 3000 W, for substrates with a diameter of 200 mm [millimeters], giving a power density of at least 0.6 W/cm^2, and preferably in the range 0.6 W/cm^2 to 10 W/cm^2. The Applicant has shown that the higher the RF power for the plasma treatment, the lower the roughness of the insulator layer.

Further, the period of this plasma treatment is advantageously at least 10 seconds, preferably in the range 10 seconds to 200 seconds, typically in the range 30 seconds to 60 seconds. The Applicant has also shown that the longer the plasma treatment period, the smoother the surface of the insulator layer.

The gas used to form the plasma may be oxygen, nitrogen or argon or a combination of these gases ($Ar + O_2$; $Ar + N_2$; $O_2 + N_2$; $Ar + O_2 + N_2$). The smoothing treatment may also be carried out in two steps, namely, for example, 60 s in argon plasma at high power, then 30 s in O_2 plasma at a more moderate power.

Preferably, the smoothing plasma treatment is done with gas atoms of the same nature as at least one of the atoms forming the treated insulator layer. For example, the result will be an oxygen plasma smoothing treatment to smooth a silicon oxide layer, and a nitrogen plasma to smooth a silicon nitride layer.

It is preferable not to modify the stochiometry and therefore the chemistry of the treated material during this type of plasma treatment.

The pressure values typically used are over 2 mTorr, preferably in the range 2 mTorr to 200 mTorr, preferably 20 mTorr to 100 mTorr, more preferably close to 50 mTorr (i.e. over 0.25 Pa, preferably in the range 0.25 Pa to 30 Pa, preferably in the range 3 Pa to 13 Pa, more preferably close to 7 Pa).

While the smoothing plasma treatment is carried out at high energy and for a particularly long period, which is not necessarily compatible with obtaining strong bonding, the situation cannot be excluded in which the initial roughness and the choice of the face to be implanted could allow parameters of the method to be employed which function both for smoothing and for activation, in particular if smoothing is carried out in two steps as described above.

The smoothing plasma treatment may also deliberately be stronger at the wafer edge (or respectively at the center) to obtain a uniform final roughness when the starting surface is rougher at the edge (or respectively the center). The skilled person will be aware of the parameters required to produce this type of differential (center/edge) correction in order to vary the plasma uniformity (pressure, center/edge power density differential, different flow rates between the center and the edge, etc).

Pre- and/or post-activation plasma cleaning:

Deep cleaning of the surface to be activated may be carried out, for example using a chemical treatment known as "RCA" to avoid any contamination.

"RCA" treatment consists in treating the surfaces in succession with the following:

- a first bath of a solution known by the acronym "SC1" (standard clean 1), which comprises a mixture of ammonium hydroxide (NH_4OH), hydrogen peroxide (H_2O_2) and deionized water;
- a second bath of a solution known by the acronym (SC2) (standard clean 2), which comprises a mixture of hydrochloric acid (HCl), hydrogen peroxide (H_2O_2) and deionized water.

Activation plasma parameters:

This is advantageously done at lower power than the smoothing plasma, for example with an RF power density equal to between 0.2 and 3 W/cm^2, preferably about 0.6 W/cm^2, to further increase the bonding energy with the receiver substrate.

Preferably, the treatment duration used will be between 5 and 60 seconds and the gas pressure inside the chamber will be about 7 Pa (50 mTorr).

Different tests have been carried out to demonstrate the effectiveness of the method according to the invention:

Test 1:

Tests were carried out on several substrates, varying the different smoothing plasma (SP) treatment parameters, so as to study the roughness of the insulator layer thus treated, both at the centre and on the edges.

This roughness measurement was made by Atomic Force Microscopy (AFM).

Tests were carried out on an insulator layer composed of silicon dioxide obtained by a TEOS LPCVD deposition. The thickness of the S_iO_2 insulator layer was 145 nm and its initial roughness before the smoothing plasma treatment was of the order of 4 to 4.5 Å RMS for a scan width of 2 µm x 2 µm.

Plasma powers of 250, 600 and 1000 W were used for times of 10, 30 and 60 seconds respectively. The results are given in the following table for an oxygen plasma, for 200 mm diameter wafers.

Table 1

Power used	Treatment duration	Measurement location	2 X 2 µm² RMS [Å]
250 W	10 s	Centre	3.64
		Edge	3.77
	30 s	Centre	3.53
		Edge	3.29
	60 s	Centre	3.07
		Edge	3.04
600W	10 s	Centre	3.64
		Edge	3.66
	30 s	Centre	2.62
		Edge	2.89
	60 s	Centre	2.37
		Edge	2.39
1000W	10 s	Centre	3.29
		Edge	3.63
	30 s	Centre	2.43
		Edge	2.55
	60 s	Centre	2.07
		Edge	2.07

Roughness values are expressed in Angstroms RMS for scan widths of 2 µm by 2 µm.

These results are shown on the graphs in figures 3 to 6.

These results are also shown in the graphs of Figures 3 to 6.

They show an initial improvement in roughness, this improvement being reinforced by the use of a high power smoothing plasma (preferably at least 600 W or, more preferably, 1000 W) and a long period.

At the end of this plasma treatment, the Applicant also observed that the silicon dioxide retained good uniformity.

The reduction in roughness was real, takes place at low temperature and avoid a subsequent chemical-mechanical polishing step.

For this reason, the treated insulator layer may be used to produce very high quality bonding onto a receiver substrate and, subsequently, layer transfer by detachment which is also of high quality, which avoids any problems with blisters, exclusion zones ("rings"), pitting or the formation of untransferred zones.

Test 2:

Other complementary tests were carried out on strained Silicon On Insulator (sSOI) substrates including a smoothed TEOS oxide inserted between a thin strained silicon layer and a silicon support layer. In this case, the smoothing power is about 1000 W for about 60 s, for 200 mm diameter wafers, corresponding to a power density of 3 W/cm^2. The gas pressure used during smoothing was 50 mTorr (about 7 Pa).

The results obtained are shown in the following table.

Table 2

Densification	Nature of treatment	Location of measurement	2 X 2 µm2 RMS [Å]
NO	Control	Centre	4.94
		Edge	5.23
	Smoothing plasma at 1000 W for 60 seconds	Centre	2.29
		Edge	2.33
YES	Implanted control	Centre	5.37
		Edge	6.3
	Smoothing plasma at 1000 W for 60 seconds followed by implantation	Centre	2.36
		Edge	-

Furthermore, comparative tests were also carried out on the above mentioned sSOI type substrates, after transfer of the thin strained silicon layer 11, some of these substrates were subjected to the above mentioned smoothing plasma treatment during their manufacture, while other substrates were not subjected to it.

The results obtained are shown on figure 7 on which N represents the number of defects and 0 and 1 show the absence and presence of the treatment by smoothing plasma respectively.

References a to f have the following meanings:

a: large untransferred zone (diameter more than 1.5 mm)

b: small untransferred zone (diameter between 0.5 and 1.5 mm)

c: micro untransferred zones (diameter less than 0.5 mm)

d: blisters

e: micro blisters

f: pitting (untransferred zones at edge of wafer).

Thus, the number of defects per wafer is reduced from about a hundred to about ten or even less, due to smoothing plasma according to the invention.

Test 3:

Other tests were carried out to study the effect of smoothing plasma on the bonding time.

The measurements made consisted of measuring the bonding time, in other words the duration of a bonding wave between a substrate made of silicon covered by an SiO_2 layer obtained by LPCVD deposition and TEOS, and a receiver substrate also made of silicon.

The tests were carried out with different batches of 200 mm diameter substrates, in which the oxides had different surface roughnesses from 3 to 6 Angstroms RMS for a scan width of 2 µm x 2 µm. These oxides had been subjected to a smoothing plasma treatment at powers of between 1000 W and 1500 W, namely power densities of between 3.2 W/cm^2 and 4.7 W/cm^2 for 200 mm diameters and for durations varying from 60 to 120 seconds.

The gas pressure in the chamber was 50 mTorr (about 7 Pa).

Figure 8 illustrates the results obtained for oxides on which the smoothing plasma treatment was not performed. It represents the duration t of a bonding wave, expressed in seconds, as a function of the number of bonding waves NO with this bonding duration.

Figure 9 illustrates the results obtained for oxides on which the smoothing plasma treatment according to the invention was carried out.

It is observed that when no smoothing plasma treatment is done, the average duration of the bonding wave or the bonding time is 43.7 seconds with a standard deviation of 33 seconds, while after a smoothing plasma,

the bonding time is reduced to 8.6 seconds with a standard deviation of 0.5 seconds.

Therefore, the smoothing plasma treatment has the effect of reducing the bonding time and consequently increasing the bonding energy making this bonding much more homogenous and reproducible.

Test 4:

The tested substrates are 200 mm diameter sSOI wafers. They were made from a donor substrate comprising a strained silicon layer with a strong surface topology on which a silicon oxide layer of the order of 1650 Angstroms (165 nm) (between 1600 and 1700 Angstroms, between 160 and 170 nm) thick was deposited by TEOS LPCVD deposition.

A distinction should be made between the topology concept and the roughness concept. Roughness is evaluated at the microscopic scale. On the other hand, the topology concept is evaluated at the macroscopic scale and denotes differences between the highest peaks and lowest peaks of the surface ("peak to valley") on an area of about 1 cm^2.

The strong strained silicon topology of the donor has an influence on the topology of the insulator layer deposited on it.

The initial roughness of the silicon oxide was 4 to 6 Angstroms RMS for a 2 µm x 2 µm scan.

The different treatments described below were applied to different batches of these donor substrates, and a silicon receiver substrate was then applied on the oxide layer of each of them, and the strained silicon layer was detached from the donor substrate to be

transferred onto the receiver substrate and to form the final substrate.

Test A	Test B	Test C	Test D	Test E
Standard smoothing	Mild smoothing	Oxide densification	Oxide densification	Oxide densification
Oxide densification	Oxide densification	Standard smoothing	Implantation of atomic species	Implantation of atomic species
Implantation of atomic species	Implantation of atomic species	Implantation of atomic species	Mild smoothing	Mild smoothing
Activation plasma (AP) of the receiver substrate	Activation plasma (AP) of the receiver substrate	Activation plasma (AP) of the receiver substrate	Activation plasma (AP) of the receiver substrate	No activation plasma of receiver substrate

Standard smoothing was obtained using an oxygen plasma formed in a chamber inside which the gas pressure was 50 mT (namely 7 Pa). This plasma was created using a radiofrequency RF generator that operates with a power density of the order of 3 watts per cm^2 and a treatment duration of 60 seconds. The oxygen flow was 75 sccm.

Mild smoothing was obtained using an oxygen plasma formed in a chamber inside which the gas pressure was 150 mT (namely about 20 Pa). This plasma was created using a radiofrequency RF generator that operates with a power density of the order of 1.5 watts per cm^2 and a treatment duration of 60 seconds. The oxygen flow was 200 sccm.

Densification of the oxide by thermal annealing was achieved using a heat treatment at about 850°C for 2 hours.

Atomic species were implanted by an implantation of ions of about 30 keV, namely a dose of the order of 6.10^{16} H^+/cm^2.

The activation plasma (AP) of the receiver substrate was done at a pressure of 50 mTorrs (about 7 Pa) at a power of 250 W, under an oxygen flow of 75 sccm (standard cubic centimetre) for about 10 seconds.

The results obtained after this layer was transferred are illustrated on figure 10.

This figure shows the number of defects observed by defect category for different substrates of the same type of test.

The legend of the figures is as follows:

+: µZNT (micro untransferred zones; size < 0.5 mm)

•: gZNT (large untransferred zones; size > 0.5 mm)

■: pZNT (small untransferred zones; 0.5 mm < size < 1.5 mm)

x: scratches (to be ignored).

After seeing the first results, particularly for tests A to C, it can be concluded that regardless of the applied plasma treatment (standard or mild) and regardless of whether it is applied before or after densification, good results can be obtained in terms of the small number of defects, provided that smoothing plasma is done before the implantation of atomic species.

After seeing tests D and E, it is observed that when the smoothing treatment is done after implantation of atomic species, the results obtained are significantly less good.

Furthermore, a comparison between tests D and E shows that activation plasma (AP) of the receiver

substrate can reduce the number of defects observed after detachment.

It is deduced that the activation resulting indirectly from smoothing done before implantation of strained Si type donor substrates is reduced or even eliminated due to the different successive treatments carried out after the smoothing plasma treatment.

The different tests carried out showed the advantages of the invention.

The effect of the smoothing plasma (SP) treatment is to reduce the roughness of the thick insulation, and the fact that it is followed by a Smart Cut® type implantation can eliminate the chemical activation effect that it would otherwise have on the insulation.

The method according to the invention is also particularly suitable for substrates with a strong topology with high "peak to valley" values, since it has been shown that the roughness of such substrates can also be reduced by this method.

Furthermore, with this type of substrate, strong topology zones are usually located on the edges and these are the locations at which defects appear during the layer transfer, if the substrate was activated. Therefore, chaining of steps in the method according to the invention that prevents activation is quite suitable.

CLAIMS

1. Method of reducing the roughness of a thick insulator layer (2), deposited on a substrate (1) intended for use in the electronics, optoelectronics or optics fields, characterized in that it comprises the following steps consisting in:

- depositing an insulator layer (2), with a thickness greater than or equal to 20 nm, with a roughness greater than or equal to 3 Angstroms RMS, for a scan width of 2 µm x 2 µm, on a first so-called "donor" substrate (1);
- carrying out a smoothing treatment (SP) on the free surface (20) of said insulator layer, using a gas plasma formed in a chamber inside which a gas pressure of more than 0.25 Pa and less than 30 Pa is established, said plasma being created using a radiofrequency generator RF which functions at a power such that it can apply a power density comprised between 0.6W/cm^2 and 10 W/cm^2 to said insulator layer (2), the duration of this smoothing treatment being in the range of 10 seconds to 200 seconds.

2. Method according to claim 1, characterized in that an embrittlement zone (10) is formed inside said donor substrate (1) to define a so-called "active" layer (11) and a reminder (12) therein.

3. Method according to claim 2, characterized in that the embrittlement zone (10) is formed by atomic species implantation and in that the smoothing plasma treatment (SP) is carried out before said atomic species implantation.

4. Method according to claim 2 or 3, characterized in that it further comprises:

- the bonding of a second so-called "receiver" substrate (3) onto said free surface (20) of the insulator layer (2).

5. Method according to claim 4, characterized in that it further comprises:
- detachment of the remainder(12) of the donor substrate (1), at the embrittlement zone, to transfer said active layer (11) and the insulator layer (2) to the receiver substrate (3).

6. Method according to claim 5, characterized in that it further comprises:
- the cleaning of the free surface (20) of the insulator layer (2),
- an activation plasma treatment (AP) of said free surface (20) of the insulator layer 30 (2).

7. Method according to claim 6, characterized in that the activation plasma treatment (AP) of said insulator layer (2) is carried out using a gas plasma formed in a chamber inside which a gas pressure of about 7 Pa is established, and in that the cleaning of the free surface (20) of the insulator layer (2) comprises a chemical cleaning.

8. Method according to any one of the previous claims, characterized in that the insulator layer (2) is a nitride, an oxynitride or an oxide.

9. Method according to any one of the previous claims, characterized in that the insulator layer (2) is an oxide deposited by a low pressure chemical vapor phase deposition technique (LPCVD).

10. Method according to claim 9, characterized in that the insulator layer (2) is a silicon dioxide (SiO_2) obtained by a low pressure chemical vapor phase deposition technique, starting from tetraethylorthosilicate (TEOS LPCVD), and deposited at a pressure in the range of 40 Pa to 200 Pa.

11. Method according to any one of the previous claims, characterized in that the smoothing treatment (SP) of the

free surface (20) of the insulator layer (2) is carried out with a gas pressure inside the chamber in the range of 3 Pa to 13 Pa and in that the gas used to form the plasma is selected from oxygen (O_2), argon (Ar), nitrogen (N_2) and a mixture of said gases, the duration of said smoothing treatment being in the range of 30 seconds to 120 seconds.

12. Method according to any one of the previous claims, characterized in that it comprises a densification anneal of the insulator (2) at a temperature of between 700°C and 1000°C, for a duration of several minutes to several hours, in an oxidising or neutral atmosphere.