# THERMAL TREATMENT OF A SEMICONDUCTOR LAYER

## FIELD OF THE INVENTION

The invention relates to a method of forming a structure comprising a layer taken off from a donor wafer, the donor wafer comprising before taken off a first layer made of a semi-conductor material comprising germanium, the method comprising the following successive steps:

(a) forming a weakness zone in the thickness of said first layer comprising germanium;

(b) bonding the donor wafer to a host wafer;

(c) supplying energy so as to weaken the donor wafer at the level of the weakness zone, this energy supply may lead to disunite the taken-off layer from the donor wafer at the level of the weakness zone and thus to take off a layer comprising the remaining part of the fist layer;

(d) treating the taken-off layer.

## BACKGROUND OF THE INVENTION

This type of layer taking-off is called Smart-Cut® and is known to those skilled in the art. In particular, details may be found in many documents that have already been published, such as for example the extract on pages 50 and 51 of the work "Silicon on Insulator technology: material tools VLSI, second edition," by Jean-Pierre Colinge published by "Kluwer Academic Publishers".

Step (a) may be carried out by simple implantation of a single atomic species (for example of hydrogen) or by co-implantation of at least two different atomic species (for example hydrogen and helium) with suitable implantation dose and energy of the species to be implanted.

Step (b) of the bonding of the donor wafer to the host wafer typically takes place on the surface of the donor wafer having undergone the

implantation, by means of a bonding layer made of dielectric material such as $SiO_2$.

The bonding techniques typically used by those skilled in the art include initial bonding by molecular adhesion. We can refer to the document "Semiconductor Wafer Bonding Science and Technology" (QY Tong and U. Gösele, Wiley Interscience Publication, Johnson Wiley and Sons, Inc.) to obtain more information.

In step (c), energy is provided in the form of heat in order to weaken the donor wafer at the level of the weakness zone. This energy supply is susceptible to lead to the disunion of the taken-off layer from the donor wafer at the level of the weakness zone.

A complementary supply of energy, in thermal and/or mechanical form, may however be necessary to effectively realise the disunion of the taken-off layer, and thus to make possible its detachment and transfer onto the host wafer.

In this way, a semiconductor on insulator structure SeOI may be formed, such as an SOI structure (in the case of the detached layer being made of silicon), SiGeOI (in the case of the detached layer being made of germanium silicon), GeOI (in the case of the detached layer being made of germanium), SGOI (in the case of the detached layer comprising a SiGe layer on which lies a strained silicon layer), or sSOI (in the case of the taken-off layer is made of strained silicon).

It can be frequently observed that after detachment of the detached layer, the latter may have quite a rough surface, as well a lower quality crystalline structure on its surface, notably due to the fact that the implantation and the detachment steps have taken place beforehand.

In reference to figure 1, a semiconductor on insulator structure 30 is shown diagrammatically (composed of a host wafer 20 covered by the detached layer 1 by means of an electrically isolating layer 5), which has, in its semiconductor part (i.e. the detached layer 1), such a reduction in the crystalline quality.

It may be observed that the detached layer 1 comprises a defective zone 1A, this defective zone 1A comprising existing crystalline defects and surface roughness.

The defective zone 1A typically has a thickness of around 150 nm for an atomic implantation of hydrogen.

Furthermore, the implantation step may have caused a reduction of the crystalline quality of the detached layer 1.

Step (d) of the treatment of the detached layer 1 is therefore necessary to remove this defective zone 1A, and thus recuperate at least part of the sound zone 1B of the layer taken 1.

For example, it is possible to use mechanical polishing or chemical-mechanical polishing (CMP) to eliminate the surface roughness, and/or sacrificial oxidation steps of the defective zone 1A.

By sacrificial oxidation, one classically understands a step comprising the operations of oxidation of the defective zone and of removal of the oxide layer thus formed by chemical etching (for instance by using hydrofluoric acid HF).

By way of illustration, such a four steps method is described in the document US2004/0053477, in which a strained silicon layer is detached from a donor wafer comprising a SiGe buffer layer. Step (a) consists of making the implantation in the buffer layer, and step (d) comprises the removal of the part detached from the buffer layer by means of surface polishing the SiGe then selective etching of the SiGe with respect to the strained Si. The selective etching permits in particular to obtain finally the desired layer with a good quality of surface finish, without too high a risk of damaging it (which could be the case if only polishing were used).

However, the chemical etching used in this step (d) may in certain cases lead to at least partial detachment problems of the bonding interface (bonding carried out in step (b). Indeed, the chemical etching of step (d) may in particular cause de-lamination at the edge of the bonding layer, which is to say attack the latter where it touches by the slice of the structure created. For example, we can mention the case of a HF treatment on an sSOI (strained

Silicon on Insulator) structure comprising $SiO_2$, buried under the strained Si, or the case of a $H_2O_2$:HF:HAc treatment (HAc being the abbreviation of acetic acid) on a SGOI structure (Strained Silicon on Silicon Germanium On Insulator), where the buried SiGe and $SiO_2$ layers are likely to be etched under the strained Si layer.

An alternative that could be envisaged to overcome the last problem would be to dilute the etching solution considerably so that its action is easier to control. However this solution is not satisfactory due to the fact that it does not totally resolve the de-lamination problem and that the method is slightly slowed down.

Moreover, this chemical etching requires prior preparation of the surface to be etched, typically carried out using mechanical polishing means. In fact, this etching preparation remains necessary to correct part of the major roughness which could subsequently lead to etching that is not sufficiently homogeneous and likely to create traversing defects or holes in the remaining layer, but also lead to the free face of the final product being rough.

Furthermore, the presence of defects in the whole thickness of the taken-off layer (and not only in the thickness of the defective zone) is also likely to cause an inhomogeneous etching.

But successive actions of polishing and chemical etching make the post-detachment finishing step (d) (as well as the entire sampling method) long, complex and costly from an economic point of view.

Of course, it will be understood that problems encountered when a selective etching is performed are relatively similar to those encountered when performing an etching operation during a sacrificial oxidation, in particular as concerns the etching inhomogeneity due to a superficial roughness and a presence of defects.

A first purpose of the invention is to reduce the duration, the economic cost and the number of treatment means during step (d), of a taken-off layer, and in particular to stop using mechanical polishing means.

A second purpose of the invention is to create a structure, such as a SeOI semiconductor on insulator structure, by taking off a layer in a semi conductor material comprising Germanium, such as in particular a SiGe layer.

A third purpose is to create such a structure from a taken-off layer of better quality.

A fourth purpose of the invention is to reduce the quantity of material wasted when treating the taken-off layer.

A fifth purpose of the invention is to propose a simple method of treating the taken-off layer that can easily be incorporated into the entire sampling Smart-Cut® type method.

## SUMMARY OF THE INVENTION

This invention attempts to overcome these problems by proposing according to a first aspect, a method forming a structure comprising a layer that is taken-off from a donor wafer, the donor wafer comprising prior to taking-off a first layer made of a semi conductor material comprising germanium, the method comprising the following steps:

(a) formation of a weakness zone in the thickness of said first layer comprising germanium bonding the donor wafer to a host wafer;

(b) bonding the donor wafer to a host wafer;

(c) supplying energy so as to weaken the donor wafer at the level of the weakness zone;

wherein step (a) is carried out by subjecting the donor wafer to a co-implantation of at least two different atomic species, and step (c) is carried out by performing a thermal treatment at a temperature between 300°C and 400°C, for a duration that can last up from 30 minutes to four hours.

Other possible characteristics of the method according to the first aspect of the invention are as follows:

- thermal treatment of step (c) is carried out at a temperature comprised between 325°C and 375°C during substantially two hours;

- the energy supply of step (c) may lead to the disunion of the donor wafer at the level of the weakness zone and thus to the taking-off of a layer comprising a part of the first layer;

- after step (c), the method further comprises a step of supplying a complementary energy adapted to disunite the donor wafer at the level of the weakness zone;

- the supply of complementary energy is of thermal and/or mechanical form;

- before step (b), the method further comprises, a step carried out by plasma activation so as to strengthen the bonding;

- the co-implantation of step (a) is a co-implantation of helium and hydrogen;

- the doses of helium and hydrogen are chosen so that the helium dose represents 30% to 70% of the total dose, and preferably 40% to 60% of the total dose;

- the low/high frequencies roughnesses, after disunion of the donor wager at the level of the weakness zone, are lower than around 15 Å RMS/30 Å RMS, measured by 500 microns profilometry/ 2*2$\mu m^2$ AFM;

- the method further comprises a step (d) adapted for treating the taken-off layer;

- step (d) comprises an etching operation of the taken-off layer;

- the etching operation is carried out during a sacrificial oxidation of the taken-off layer;

- the donor wafer comprises before take-off a second layer in a material different from that of said first layer and the etching operation is a selective etching of the part of the first layer remaining after detachment with respect to said second layer;

- before said selective etching, a sacrificial oxidation of at least a part of the remaining part of the first layer is carried out so as to remove material from said remaining part and to strengthen the bonding interface;

- the method further comprises, after step (d), a crystalline growth adapted to thick said second layer;

- the first layer is made of $Si_{1-x}Ge_x$ with $0<x\leq 1$ and the donor wafer comprises a second layer made of elastically strained Si;

- the donor wafer comprises a support substrate made of bulk Si, a buffer structure made of SiGe, a first layer comprising $Si_{1-x}Ge_x$ ($x \neq 0$) and a second layer made of strained Si;

- the first layer is made of $Si_{1-x}Ge_x$ and the donor wafer comprises a second layer made of strained Si and a third layer made of $Si_{1-x}Ge_x$ on the second layer;

- step (d) comprises a selective etching of the remaining part of the first layer with respect to the second layer;

- the donor wafer comprises a support substrate made of bulk Si, a buffer structure made of SiGe, and a multi-layer structure alternatively comprising first layers of $Si_{1-x}Ge_x$ ($x \neq 0$) and second layers made of strained Si, so as to be able to take off several times from the same donor wafer;

- the method further comprises, prior to step (a), the formation of the strained layer at a deposit temperature of between around 450°C (842°F) and around 650°C (1,202°F);

- the method further comprises, prior to step (b), a step of forming a bonding layer on the donor wafer and/or on the host wafer, the bonding layer comprising an electrically insulating material, for example such as $SiO_2$, $Si_3N_4$ or $Si_xO_yN_z$.

According to a second aspect, the invention proposes an application of the said method of forming a structure, for the formation of a semiconductor-on-insulator structure such as a sSI, SGOI, SiGeOI or GeOI structure.

According to a third aspect, the invention proposes a semiconductor on insulator structure obtained after carrying out all of the steps (a), (b) and (c) of the method according to the first aspect, and after removing the contact of the taken off layers with the remaining part of the donor wafer, this structure having low/high frequencies surface roughness of less than about 30ÅRMS, as measured by profilometry 500 $\mu$m and AFM 10 × 10µm², in any place of the wafer.

## BRIEF DESCRIPTION OF THE FIGURES

Other characteristics, aims and advantages of the invention will become clear upon reading the following detailed description of the application of preferred methods of it, given by way of non-restrictive examples and made in reference to the appended diagrams in which:

Figure 1 shows a diagrammatical cross section of a semiconductor on insulator structure obtained after the application of a Smart-Cut® method according to the state of the technique.

Figure 2 shows a cross sectional view obtained by TEM by the applicant of a semiconductor on insulator structure obtained after application of the method of the invention.

Figures 3a to 3e show diagrammatically the different steps of a method of the invention to form a structure comprising a layer taken using Smart-Cut®.

Figures 4a and 4b show diagrammatically a first variant according to the invention.

Figures 5a and 5b show diagrammatically a second variant according to the invention.

Figure 6 illustrates the presence of pores type defects in a structure for which a post disunion thermal treatment at 600°C has been carried out

## DETAILED DESCRIPTION OF THE INVENTION

Examples of embodiments of methods according to the invention are described below, as well as applications according to the invention, based on layers taking-off using Smart-Cut® comprising germanium, such as SiGe layers.

In reference to figures 3a to 3e, is shown a first method of taking-off a first layer 1 in $Si_{1-x}Ge_x$ (where $x \in [0;1]$) and a second layer 2 of elastically strained Si from a donor wafer 10, to transfer them to a host wafer 20 according to the invention.

In reference to figure 3a, a donor wafer 10, comprising the first layer 1 made of $Si_{1-x}Ge_x$ and the second layer 2 of elastically strained Si, is illustrated.

Classically, a donor wafer 10 including $Si_{1-x}Ge_x$ comprises a bulk Si substrate 5 on which has been formed for example by crystalline growth a buffer structure of SiGe (not shown) made up of different layers. In particular, the latter may have a gradual evolution in thickness in its composition of Ge, starting from 0% at the bulk Si substrate level to around 100x% at the level of the interface with the first layer 1 made of $Si_{1-x}Ge_x$ (it also preferably being formed by crystalline growth).

A second layer 2 of strained Si is formed on the first layer 1 in $Si_{1-x}Ge_x$. In a first case, the growth of the second layer 2 is carried out in situ, directly in continuation of the formation of the first layer 1. In a second case, the growth of the second layer 2 is carried out after a light step of preparation of the surface of the underlying adaptation layer 2, for example by CMP polishing.

The second layer 2 made of Si is advantageously formed by epitaxy using known techniques such as Chemical Vapour Deposition (CVD) and Molecular Beam Epitaxy (MBE) techniques.

The silicon contained in the second layer 2 is then obliged by the first layer 1 to increase its nominal mesh parameter to make it more or less identical to that of its growth substrate and thus to present internal elastic strain tensions. It is necessary to form a quite thin second layer 2: if the layer is too thick, thicker than a critical equilibrium thickness, would cause a relaxation of the strain in the film thickness towards the nominal lattice parameter of the silicon and/or generation of faults. We can refer to the document entitled "High mobility Si and Ge structures" by Friedrich Schaffler ("Semiconductor Science Technology", 12 (1997) 1515-1549) for more details on this subject.

However, in the particular case of a deposit of strained material at a sufficiently low temperature, it is possible to form such a second strained layer 2 having a more important thickness (the critical balance thickness is

indeed linked to the deposit temperature: it is all the more important as the deposit is carried out at low temperature).

In reference to figure 3b, a weakness zone 4 is then formed in the donor wafer 10 underneath the second layer 2. In particular, an implantation may be performed in order to form the weakness zone in the thickness of the first layer 1 made of $Si_{1-x}Ge_x$ (as it is shown in figure 3b).

This weakness zone 4 is formed by implantation of atomic species whose dosage, nature and energy are chosen so that a depth of implantation and a level of fragility are determined.

In particular, the parameters determining the implantation of atomic types are adjusted so as to minimise the surface roughness which appears at the level of the weakness zone 4 after detachment. In fact, the extent of the post-detachment surface roughness is partially caused by the parameters defining the implantation used, as we will subsequently see.

Thus, according to the invention, the implantation of atomic species is a co-implantation of atomic species (i.e. the implantation of, principally, at least two different atomic elements), such as for example a co-implantation of hydrogen, helium or argon or another rare gas or another suitable gas.

In the case of a co-implantation, the applicant has in fact observed that the weakness zone 4 is generally thinner than in the case of a simple implantation.

The recourse to co-implantation will especially allow to obtain a post detachment roughness lower to that obtained when implantation of a simple implantation of helium or hydrogen.

One finds here one of the advantages of co-implantation which allows for the taking-off of a thin layer using a total dose of co-implanted species lower than the dose to be used when a single species is implanted. The total dose in co-implantation thus typically represents 1/3 of the single species implantation dose.

The energy of the implantation is chosen so as to have an implantation depth neighbouring that of the depth of the first layer 1.

Thus for a co-implantation with helium of around $1.10^{16}/cm^2$ and energy of between 50 and 90 keV and hydrogen at $1.10^{16}/cm^2$ and energy of between 20 and 60 keV, we can obtain a depth of implantation of around 300 to 600 nanometres.

Generally speaking, helium and hydrogen doses are chosen so that the helium dose represents 30% to 70% of the total dose, and preferably 40% to 60% of the total dose.

In reference to figure 3c, a bonding step of a host wafer 20 with the side of the donor wafer 10 having undergone the co-implantation is carried out.

The host wafer 20 may be made of bulk Si or other materials.

Prior to the implantation step, a bonding layer may be formed, such as a layer comprising $SiO_2$, $Si_3N_4$, $Si_xO_yN_z$ on one and/or the other of the respective surfaces to be bonded. In the case this bonding layer has to be formed onto the donor wafer, the technique used to form this bonding layer may be a deposit, in order to avoid any deterioration of the strains in the second layer 2 or any diffusion consequently in the first layer 1.

Prior to bringing the host wafer 20 into contact with the donor wafer 10, the surfaces to be bonded may possibly be prepared, using known surface cleaning and polishing techniques such as SC1 and SC2 solutions, ozone solutions etc.

The bonding itself may be firstly carried out by molecular adhesion, by being able to take account of the hydrophily of each of the two surfaces to be bonded.

It is also possible to use plasma activation of one or both of the two bonding surfaces just before bonding.

A plasma activation permits in particular to create handling bonds, for example on an oxide surface, on the surface(s) to be treated, and therefore increase the bonding forces to be made and reduce the number of defects at the bonding interface 6, as well as their influence on the quality of the bonding.

Such strengthening of the bonding interface 6 will also have the advantage of therefore making this interface much more resistant to chemical attacks from later etching (used when finishing the surface of the layer taken off, for instance during a selective etch operation or a sacrificial oxidation operation) and avoid delamination problems at the edges as previously discussed, which may typically appear for a bonding energy below approximately 0.8 J/m².

In particular, the plasma activation can be used so that in the end, after bonding and after taking-off, the bonding energy is greater than or equal to approximately 0.8 J/m².

The plasma may be obtained for example from an inert gas, such as Ar or $N_2$, or from an oxidising gas such as $O_2$.

The plasma activation can typically be carried out at ambient temperature, below approximately 100°C. The use of this technique therefore also has the advantage of not causing any notable problems of diffusing Ge from the first SiGe layer 1 to the second strained Si layer (generally speaking Ge diffusion starts becoming significant in the thickness of the neighbouring layers for much higher temperatures, typically around 800°C or more).

The duration of the plasma treatment is very quick, typically less than one minute.

The equipment used will be for example standard plasma etching equipment of the RIE or ICP-RIE types or other.

After step (b) of bonding, energy is supplied under thermal form during step (c) in order to weaken the donor wafer at the level of the weakness zone.

It has to be noted that the thermal budget (typically temperature and length) of this energy supply (hereafter said "weakening thermal treatment") can in particular, but not necessarily, lead to the disunion of the taken-off layer from the donor wafer at the level of the weakness zone.

The weakening thermal treatment is typically carried out at a temperature lower than 800°C, but all at least lower than a limit temperature from which the Ge diffusion in the neighbouring layers becomes prejudicial.

In reference to figure 3d, is shown the disuniting step of the donor wafer 10 into a first part 10' comprising a remainder of the first layer 1" and into a second part 30 comprising the other part of the first layer 1' and the second layer 2.

As already mentioned above, this disunion can be performed thanks to the energy supply of the weakening thermal treatment.

However, when the energy supply of the weakening thermal treatment is not sufficient to lead to the disunion, this latter can be carried out thanks to a complementary supply of energy (for instance under thermal and/or mechanical form) sufficient to cause, at the level of the weakness zone 4, thermal effects on the gaseous types enclosed there causing the rupture of weak links.

Generally speaking, disuniting may be obtained at temperatures of between around 300°C and around 600°C for durations of varying lengths which depend on whether the temperature is lower (longer length) or higher (shorther length).

Optionally, or in replacement of the plasma activation, a thermal treatment can be carried out directly after disunion, in order to strengthen the bonding interface 6.

In the case of this bonding strengthening heat treatment being used in addition to the plasma activation, it is therefore possible to make sure that the combined effects of these two treatments achieve the desired objectives, an in particular a bonding energy sufficient to make the bonding interface 6 resistant to chemical attack from later etching, and thus to avoid delamination problems on the edges, as previously described. We can thus combine the two treatments to strengthen the bonding interface 6 to obtain a bonding energy greater than or equal to approximately 0.8 J/m².

In any case, the heat treatment for strengthening the bonding interface 6 is carried out at a temperature $T_2$ chosen below the temperature above which the Ge diffuses significantly into the thickness of the second layer 2.

The heat treatment to strengthen the bonding interface 6 is carried out at a temperature $T_2$ lower than or equal to approximately 800°C.

Temperature $T_2$ can for instance be between 350°C and 800°C, maintained during 30 minutes up to four hours.

This bonding strengthening thermal treatment can in particular, without this being restrictive, be carried out during a step of sacrificial oxidation, during which an oxidation of the surface of the remainder of the first layer 1' (typically SiGe layer) is carried out around 600/800°C, and then a removal of the oxide thus formed is carried out. In such a case, the sacrificial oxidation has thus for double objective to reinforce the bonding interface and to proceed to the removal of at least a part of the defective zone.

This heat treatment to strengthen the bonding is carried out in an inert atmosphere (such as an Ar or $N_2$ atmosphere) that is oxidising or slightly oxidising.

The applicant has thus observed that by using such a step of bonding interface 6 strengthening, in particular when it is followed by a co-implantation step, the taken off layers then have:

- an improved crystalline quality in their parts damaged during the implantation (in reference to figure 3b) and during disuniting (in reference to figure 3d);
- a smoothed surface, in particular for high frequency roughness (HF roughness);
- a bonding energy greater than approximately 0.8 J/m² (without plasma activation).

It has to be noted that the decrease of the defective zone 1A thickness is more particularly observed when the weakness zone is formed by co-implantation. In the same way, the post detachment surface roughness is also significantly decreased when a co-implantation is performed rather than the implantation of a single species.

This is mainly due to the fact, already mentioned above, that the total dose in co-implantation is much lower than the implanted dose when a single species is implanted.

Thus co-implantation has the advantage, compared to the implantation of a single species, to reduce the thickness of the defective zone, which in

particular makes it possible to reduce or simplify the finishing treatments implemented after detachment. In the same way, co-implantation also has the advantage of reducing roughness, which also makes it possible to facilitate the finishing treatments.

However, such a bonding strengthening heat treatment can not be completely satisfactory. The Applicant has noted, in particular for thermal treatments carried out at 600°C in order to strengthen the bonding interface, the presence, close to the surface, of a low density of "pores" and other types of defects.

They are secondary defects consisting mainly of three-dimensional zones of low density in the material and whose size (roughly the diameter) is about 3-4 nm. The origin of the these defects is not certain, but it seems that it is related to the bonding strengthening heat treatment (typically at 500°C or 600°C). In addition, this bonding strengthening treatment being realized in furnaces in which the temperature is not entirely uniform (one can then observe a temperature gradient at the level of the surface of the wafer, for example a 300 mm in diameter wafer, the wafer being positioned vertically in the furnace), it may be that the distribution of defect on the surface is not homogeneous, which poses a problem to carry out an etching operation.

Figure 6 shows two views obtained by TEM (respectively on a scale of 10nm for the top view and of 2nm for the bottom view) of an intermediate structure (intended to form a final sSI structure) which was subjected to such a post-disunion thermal treatment at 600°C and in which pores are observed.

But these crystalline defects are not desirable insofar as they are likely to locally modify etching and/or oxidation speeds during the finishing operations likely to be performed after detachment. These operations are then made more complex, or then require the implementation of a mechanical treatment aiming at carrying out a removal of material (polishing /planarisation), which, as mentioned previously, is not desirable because it has an over cost and is likely to compromise the uniformity characteristics of the taken-off layer.

In order to prevent the appearance of these pores and other defects, the Applicant proposes to carry out the step of weakening thermal treatment by carrying out a low temperature annealing, at a temperature ranging between 300°C and 400°C, for example at approximately 350°C (+/-25°C), for a length of time ranging between approximately 30 minutes and approximately four hours, for example during approximately two hours.

Of course, it will have been understood that as a function of the thermal budget (couple temperature/length), said weakening treatment can result or not in disuniting the taken-off layer from the donor wafer. If the weakening treatment does not result in disuniting the taken-off layer from the donor wafer, a supply of complementary energy, under thermal and/or mechanical form, can be carried out. Generally speaking, it is a question here of locally bringing energy (in time and/or space) per application of a mechanical tool or of a short or localised heating so as to initiate the detachment at the level of the weakness zone, detachment which then can auto-propagated. For further details, one can refer to patent applications PCT/FR0402779 and PCT/FR0402781 not yet published.

In particular, a complementary supply of energy under mechanical form can in such a case figure be a rather weak complementary supply, sufficient to initiate the detachment.

The Applicant has indedd noted that the recourse to such a weaken treatment allows, in the case of a co-implantation, to limit the presence of defects.

Results of roughnesses measurement on a SGOI structure with 20% of Ge, carried out by the Applicant are presented hereafter and relate to the case of a weakening heat treatment performed during approximately two hours, at a temperature substantially equal to 350 °C. In these experiments, no heat treatment, post disunion, for strengthening the bonding interface or for curing was performed.

The Applicant thus carried out roughness measurements both low frequencies (realized using the Dektak® profilometry tool of the company Veeco Instruments Inc, 500 µm of sweeping) and high frequencies (realized

by sweeping a surface area of 2*2µm² with the point of an atomic force microscope AFM).

Results of these measurements are expressed in RMS ("Root Mean Square") average values.

In the following table, by way of comparison, one also deferred the roughnesses measured on a identical SiGeOI structure (at 20% Ge) right after disunion at 500°C during 30 minutes, following simple implantations or co-implantations, and a thermal treatment post-disunion for strengthening the bonding at 600°C.

| Nature of the implantation Recovering treatment | Low Frequencies roughness | High frequencies roughness |
|---|---|---|
| | | |
| H only implantation 30 keV- $6.10^{16}$/cm² | | |
| Post-desunion treatment at 600°C during 1h | 18 Å RMS | 29,7 Å RMS |
| | | |
| He/H Co-Implantation He: 56 keV- $1.10^{16}$/cm² H : 50 keV- $1.10^{16}$/cm² | | |
| Post-desunion treatment at 600°C during 1h | 13 Å RMS | 25,6 Å RMS |
| Weakening treatment at 350 °C during two hours | 12 Å RMS | 25,6 Å RMS |

This table shows that in the case of a co-implantation, a weakening thermal treatment at 350°C makes it possible to reach levels of low roughnesses and high frequencies equivalents with those observed for a post-disunion treatment at 600°C.

However, in the case of a weakening thermal treatment at 350°C, defects of the "pores" types are not observed and a good surface defectivity uniformity is reached, and that in any place of the wafer (that is on the entirety of the diameter, typically 200 or 300 mm, of the wafer).

These good results seem in particular obtained owing to the fact that the low temperature treatment (typically around 350°C) is likely to cause only a low amplitude temperature gradient (in comparison with that observed for a higher temperature treatment, for example at 500°C or 600°C) in the furnace.

Thus, the detachment parameters identified here (co-implantation, low temperature weakening treatment) make it possible in particular to reduce the thickness of the defective zone, to limit the presence of defects and to minimize the surface roughness. Under such conditions, the eventual post-detachment finishing operations are facilitated; in particular, the recourse to the use of an operation of polishing /planarisation is avoided or all at least limited.

In reference to figure 2, a SiGeOI structure 30 with Ge 20% (photographed by TEM) obtained by the Applicant following a transfer of a simple layer of $Si_{0,8}$ $Ge_{0,2}$ in which the weakness zone was formed, and following a weakening thermal treatment at 350°C, shows a taken-off layer 1 in $Si_{0,8}$ $Ge_{0,2}$ (i.e. the equivalent of the said first layer 1 and second layer 2 joined together, discussed before in reference to figures 3a to 3e), covers a $SiO_2$ layer 5 and includes very few crystalline defects and very few roughnesses compared to that of the semiconductor-on-insulator structure of figure 1.

One will in particular notice disproportion between the thickness of the defective zone 1A of the taken-off layer 1 in reference to figure 1 and that of the cured taken-off layer 1 in reference to figure 2.

In the same way, and for a same taken-off layer thickness 1 for figure 1 and figure 2, the healthy zone 1B is much more significant in proportion in the SiGeOI obtained according to the invention than in the semiconductor-on-insulator of the state of the art.

Returning to the description of the method illustrated by the figures 3a-3e, and in reference to figure 3e, after withdrawal of the remaining part of the donor wafer 10' from the contact with the taken-off layers 1' and 2, a structure 30 is obtained comprising the host wafer 20, the second layer 2 and the remaining part of the first layer 1'. This structure 30 has an improved crystalline quality and reduced roughness, without having need for an intermediate polishing operation. In particular, the remaining part of the first layer 1' has no pores or other defects, notably close to the surface.

In the case of an electrically insulating layer being formed beforehand, between the second layer 2 and the host wafer 20, then a SiGe/sSOI or Ge/sSOI structure is obtained.

A finishing step is then used to remove the slight roughness and few remaining crystalline defects at the surface, such as the use of chemical etching, for instance in the framework of a selective etching of a layer with respect to anther or of an etching carried out during a sacrificial oxidation.

The mechanical polishing means used prior to the chemical etching to reduce the surface roughness (and therefore to make the different points of the etching more homogeneous), do not necessarily need to be included. Indeed the implementation of a co-implantation ensures a much smoother sampling surface than hat obtained by simple implantation.

The $Si_{1-x}Ge_x$ layer 1' may possibly be removed in order to obtain a final sSOI structure (see figure 3a). It is then possible to make the strained silicon of this structure thicker by epitaxy.

To remove the layer 1' of $Si_{1-x}Ge_x$ selectively, it is possible to use selective etching by using for example $HF:H_2O_2:CH_3COOH$, SC1 ($NH_4OH/H_2O_2/H_2O$) or HNA ($HF/HNO_3/H_2O$).

A selectivity of around 40:1 between the SiGe and the sSi may be obtained with $CH_3COOH/H_2O_2/HF$.

An example of concentration that may be chosen for the $CH_3COOH/H_2O_2/HF$ such that the ratio $H_2O_2/HF$ is comprised between 1/1 (very concentrated) and 20/1.

The length of the etching is directly correlated with the speed of etching. It is typically around 5 minutes for 800A to be etched with $CH_3COOH/H_2O_2/HF$.

Thus, the co-implantation and the use of the low temperature weakening thermal treatment having considerably reduced the surface roughness and the non-uniformities of thickness in the taken-off layers 1' and 2, it is possible to use more or less the same selective etchings as those of the state of the technique, but by also eliminating the disadvantages that they

can present, such as the need to use beforehand mechanical polishing means.

In the case of one or more bonding layers being buried under the bonding interface 6, a heat treatment may possibly then be used to strengthen the bonding further, in particular by creating covalent links.

This bonding strengthening heat treatment may be carried out here at a temperature of over 800°C, given that there is no more SiGe or Ge in the structure 30, and that there are therefore no more problems of diffusion of Ge (the remainder of the first layer 1' having been completely removed).

Possibly, a subsequent step pf crystalline growth may be used (for example MBE or CVD epitaxy) to thicken the second layer of strained Si.

According to a second variant of the invention, in reference to figures 4a and 4b, the donor wafer 10 comprises prior to taking off a first layer 1 of $Si_{1-x}Ge_x$, then a second layer 2 of strained Si and a third layer 3 of $Si_{1-x}Ge_x$ that is situated on the second layer 2. The weakness zone is then formed according to the invention underneath the second layer 2, for example in the first layer 1. Selective etching of the $Si_{1-x}Ge_x$ may then be used after separation in compliance with what has been already seen, so as to create finally a SGOI structure 30 (Strained Silicon On SiGe On Insulator structure, as shown on figure 4b) with a first layer 1 of $Si_{1-x}Ge_x$ and a second layer 2 of strained Si.

Optionally, it is possible to thicken the second layer 2 of strained Si by crystalline growth.

Optionally and alternatively, a second selective chemical etching of the strained Si may be carried out, for example by means of chemical types based for example on KOH (potassium hydroxide), $NH_4OH$ (ammonium hydroxide), TMAH (tetramethyl ammonium hydroxide) or EDP (ethylene diamine / pyrocathecol / pyrazine). In this case, the second layer 2 made of strained Si only plays the role of a stop layer protecting the third $Si_{1-x}Ge_x$ layer 3 from the first chemical attack. A SiGeOI structure (not shown) is then obtained. A layer of strained Si can be possibly grown on the SiGeOI, this

new strained layer may then have a better quality crystalline structure than the second layer 2 which has previously been etched.

According to a third variant of the invention, in reference to figures 5a and 5b, the donor wafer 10 comprises prior to taking-off a multi-layer structure alternatively comprising first layers 1A, 1B, 1C, 1D, 1E in $Si_{1-x}Ge_x$ ($X \neq 0$) and second layers 2A, 2B, 2C, 2D, 2E in strained Si. We can thus carry out a number of takings-off according to the invention, from the same donor wafer 10, each taking-off being then followed by recycling of the remaining part of the donor wafer 10 in order to prepare it for a new taking-off. In this way, a first sSOI structure 30A and a second sSOI structure 30B will for example be formed from the same donor wafer 10. This type of taking-off is taught in the document US2004/0053477.

According to one particular embodiment of the invention, each strained layer (referenced "2" in figures 3a to 3e, "1" in figures 4a and 4b, and "2A", "2B", "2C", "2D" or "2E" in figures 5a and 5b) of the donor wafer is thick, which is to say that it has a relatively important thickness without having the relaxation of its elastic strains. This has been made possible thanks to the formation by low temperature epitaxy. For example, a layer of strained Si deposited at temperatures of between approximately 450°C and 650°C on a growth support of $Si_{0.8}Ge_{0.2}$ can typically reach a thickness of between approximately 30 nm and 60 nm.

If such a thick strained layer is formed in this way, then care must be taken not to exceed a certain limit temperature (which is situated around the deposit temperature) in the following treatments, and in particular the treatments occurring between the deposit of the layer and the detachment of the latter, carried out by Smart-Cut®, in order to avoid relaxing of the strains.

Thus, in this case of thick strained layers, plasma activation prior to bonding (as discussed earlier) will be advantageously used and typically carried out at an ambient temperature lower than approximately 100°C. Furthermore, at least one layer of dielectric material bonding, such as $SiO_2$, is advantageously formed on one or both of the two surfaces to be bonded,

this layer made of dielectric material subsequently helping (i.e. after separation) to conserve the elastic strains.

Of course, those skilled in the art can easily transpose the invention presented above to other materials than $Si_{1-x}Ge_x$ or strained Si, given that he knows the properties and physical grandeurs associated to these materials.

For example, by retracing the steps previously described, in reference to figures 3a to 3e, those skilled in the art could create a final structure 30 made of AsGa on insulator, if he chooses a donor wafer 10 whose first layer 1 is made of Ge and the second layer 2 made of AsGa, if he implants (as described above) in the Ge of the first layer 1, if he then transfers the remainder 1' of the Ge and the second layer 2 of AsGa to a host wafer 20 by means of an electrically insulating surface, and if he selectively removes the remainder 1" of Ge by using known selective etching techniques.

Similarly, a structure GaN-on-insulator can be for example manufactured from a donor wafer 10 comprising a first layer 1 made of SiC or Si (111) and a second layer 2 made of GaN. One or several stop layers made of AlGaN and/or AlN may possibly be provided in the GaN layer. After removal of the second layer 2 made of GaN, a selective etching comprising the removal of the GaN located above the stop layer can be used.

Thus, for example, dry etching using a plasma gas comprising $CH_2$, $H_2$ and possibly Ar, can etch the GaN quicker than AlN.

We can then possibly remove the stop layer to obtain finally a layer of GaN with little surface roughness and very homogeneous thickness.

We can also in the same way adapt the method according to the invention to other taken off layers in III-V or II-VI alloys.

We can also extend all of these materials to those including carbon in small quantities (around 5%) or doping agents.

## CLAIMS

1. Method of forming a structure (30) comprising a layer (1', 2) that is taken-off from a donor wafer (10), the donor wafer comprising prior to taking-off a first layer (1) made of a semi conductor material comprising germanium, the method comprising the following steps:

(a) formation of a weakness zone (4) in the thickness of said first layer (1) comprising germanium bonding the donor wafer to a host wafer;

(b) bonding the donor wafer to a host wafer;

(c) supplying energy so as to weaken the donor wafer (10) at the level of the weakness zone (4);

wherein step (a) is carried out by subjecting the donor wafer to a co-implantation of at least two different atomic species, and step (c) is carried out by performing a thermal treatment at a temperature between 300°C and 400°C, for a duration that can last up from 30 minutes to four hours.

2. Method according to the preceding claim, wherein the thermal treatment of step (c) is carried out at a temperature comprised between 325°C and 375°C during substantially two hours.

3. Method according to any one of the preceding claims, wherein the energy supply of step (c) may lead to the disunion of the donor wafer (10) at the level of the weakness zone (4) and thus to the taking-off of a layer (1', 2) comprising a part of the first layer (1').

4. Method according to the preceding claim, wherein after step (c), the method further comprises a step of supplying a complementary energy adapted to disunite the donor wafer (10) at the level of the weakness zone (4).

5. Method according to the preceding claim, wherein the supply of complementary energy is of thermal and/or mechanical form.

6. Method according to any one of the preceding claims, wherein before step (b), it further comprises, a step carried out by plasma activation so as to strengthen the bonding.

7. Method according to any one of the preceding claims, wherein the co-implantation of step (a) is a co-implantation of helium and hydrogen.

8. Method according to any one of the two claims, wherein the doses of helium and hydrogen are chosen so that the helium dose represents 30% to 70% of the total dose, and preferably 40% to 60% of the total dose.

9. Method according to any one of the preceding claims, wherein the low/high frequencies roughnesses, after disunion of the donor wager at the level of the weakness zone, are lower than around 15 Å RMS/30 Å RMS, measured by 500 microns profilometry/ 2*2$\mu m^2$ AFM.

10. Method according to any one of the preceding claims, further comprising a step (d) adapted for treating the taken-off layer.

11. Method according to the preceding claim, wherein step (d) comprises an etching operation of the taken-off layer.

12. Method according to the preceding claim, wherein the etching operation is carried out during a sacrificial oxidation of the taken-off layer.

13. Method according to claim 11, wherein the donor wafer (10) comprises before take-off a second layer (2) in a material different from that of said first layer (1) and the etching operation is a selective etching of the part of the first layer remaining after detachment with respect to said second layer.

14. Method according to claim 13, wherein before said selective etching, a sacrificial oxidation of at least a part of the remaining part of the first layer is carried out so as to remove material from said remaining part and to strengthen the bonding interface.

15. Method according to any one of the two preceding claims, further comprising, after step (d), a crystalline growth adapted to thick said second layer (2).

16. Method according to any one of the preceding claims, wherein the first layer (1) is made of $Si_{1-x}Ge_x$ with $0<x\leq 1$ and the donor wafer comprises a second layer (2) made of elastically strained Si.

17. Method according to any one of claims 1 to 15, wherein the donor wafer (10) comprises a support substrate made of bulk Si, a buffer structure made of SiGe, a first layer (1) comprising $Si_{1-x}Ge_x$ ($x \neq 0$) and a second layer (2) made of strained Si.

18. Method according to any one of claims 1 to 15, wherein the first layer (1) is made of $Si_{1-x}Ge_x$ and the donor wafer (10) comprises a second layer (2) made of strained Si and a third layer (3) made of $Si_{1-x}Ge_x$ on the second layer (2).

19. Method according to the preceding claim, wherein step (d) comprises a selective etching of the remaining part of the first layer (1) with respect to the second layer (2).

20. Method according to any one of claims 16 to 20, wherein the donor wafer (10) comprises a support substrate made of bulk Si, a buffer structure made of SiGe, and a multi-layer structure alternatively comprising first layers (1A, 1B, 1C, 1D, 1E) of $Si_{1-x}Ge_x$ ($x \neq 0$) and second layers (2A, 2B, 2C, 2D, 2E)

made of strained Si, so as to be able to take off several times from the same donor wafer (10).

21. Method according to any one of claims 16 to 21, further comprising, prior to step (a), the formation of the strained layer at a deposit temperature of between around 450°C (842°F) and around 650°C (1,202°F).

22. Method according to any one of the preceding claims, further comprising, , prior to step (b), a step of forming a bonding layer on the donor wafer (10) and/or on the host wafer (20), the bonding layer comprising an electrically insulating material, for example such as $SiO_2$, $Si_3N_4$ or $Si_xO_yN_z$.

23. Application of the method according to the preceding claim to the formation of a semiconductor-on-insulator structure such as a sSI, SGOI, SiGeOI or GeOI structure.

24. Semiconductor on insulator structure (30) obtained after carrying out all of the steps (a), (b) and (c) of the method according to claim 1, and after removing the contact of the taken-off layers (1', 2) with the remaining part of the donor wafer (10'), this structure having low/high frequencies surface roughness of less than about 30ÅRMS, as measured by profilometry 500 $\mu$m and AFM 10 × 10µm², in any place of the wafer.