THERMAL TREATMENT OF A SEMICONDUCTOR LAYER

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

(a) implanting atomic species to form a weakness zone in the donor wafer at a given depth;

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

(c) supplying energy so as to detach the layer from the donor wafer at the weakness zone;

(d) treating the detached layer.

This type of layer taking-off is also 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 (b) of the bonding of the host wafer (of the taken-off layer) 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.

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

Typically, the energy is at least partially provided, during step (c), in thermal form. It is then that the thermal budget (the temperature/duration combination of the heat treatment) must be considered to determine the moment at which the layer to be removed will be detached.

It can be observed that after detachment of the taken-off layer, the latter may have quite a rough surface, as well a lower quality crystalline structure on its surface, due especially 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 taken-off layer 1 by means of an electrically isolating layer 5), which has, in its semiconductor part (i.e. the taken-off layer 1), such a reduction of the crystalline quality.

It may be observed that the taken-off 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.

Furthermore, the implantation step may have caused a reduction in the crystalline quality in the layer to be taken off 1.

The defective zone has to be completely removed after detachment, in particular due to the defects present within the taken-off layer. It is thus usual to take-off a layer of more important thickness in order to completely eliminate these defects during finishing operations performed after detachment. For instance, the formation of a structure comprising a 500 angstroms thick taken-off layer necessitates the transfer of 2000 to 2500 angstroms and the removal of 1500 to 2000 angstroms, for instance by polishing, selective etching or sacrificial oxidation.

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

Typically, firstly oxidation of the defective zone 1A is used, that is subsequently removed by means of chemical etching using hydrofluoric acid

HF (thus creating a treatment called sacrificial oxidation) then finishing, for example by mechanical polishing or chemical-mechanical polishing.

Such a treatment step (d) of the layer removed 1 is consequently costly and complex from an economic point of view.

Furthermore, the use of these treatment means requires that the negative of the donor wafer be systematically removed to obtain access to the surface of the layer removed 1, and therefore requires the wafers to be removed from the furnace (in which the heat treatment of step (c) has been carried out), which is a loss of time, extra handling of the wafers and the need to use suitable equipment.

The document FR 2,842,349 attempts to overcome these problems by including in the layer to be removed made of SiGe, and between the future defective zone 1A and the underlying future sound zone 1B, a stop layer made of Si, in order to improve the finishing operations used during step (d), by means of selective double etching (of the defective zone 1A and the stop layer) which substantially reduces the roughness measured depending on their maximum values (peaks and valleys) and depending on their quadratic values (in Angstroms RMS) on the surface of the sound zone 1B made of SiGe.

However, selective etching is never perfect and when the edge of the first chemical etching arrives at the interface between the defective zone 1A and the stop layer, roughness remains, this chemical etching therefore treats the surface of the stop layer unequally. Whereas, the latter is in general not very thick, the first selective etching can pass through it, and start to attack the underlying sound zone 1B considerably. In this same document, it is also proposed to precede the selective etching by polishing in order to eliminate some of these potential problems. However the combination of polishing and selective etching makes these operations more complex and longer, with an economic cost that is not necessarily profitable.

In the document FR 2,842,350, the layer removed 1 is composed of a sound zone 1B made of strained Si and a defective zone 1A in SiGe, this latter zone being then selectively removed with respect to the sound zone 1B.

We find here a problem that is analogous to the previous one when the edge of the etching reaches the sound zone 1B, the latter being unequally etched on the surface.

It is further mentioned that it has also been proposed to perform the step (a) of implanting by implanting several atomic species (typically by performing an implantation of helium and an implantation of hydrogen). This type of implantation is hereafter designated by the term of co-implantation.

Performing a co-implantation indeed allows for a total dose of co-implanted species to be used lower than when a single species is implanted. The total dose in co-implantation thus typically represents 1/3 of the dose in single species implantation. It results from this decrease in total implanted dose a decrease of the defective zone thickness which in particular allows to decrease or to simplify the finishing treatments performed after detachment.

However, as it has been shown by the Applicant in its PCT application filed on September 21, 2004 under n° IB2004003300 (and not yet published), and which teaching has been made available to the public online on the IP.com site on March, 1 2005 under reference IPCOM000083333D, in relation to co-implantation within a Si layer, the co-implantation parameters that help minimizing roughness lead to the formation of certain defects (such as blisters at the bonding interface, or crystalline defects within the thickness of the taken-off layer), and reciprocally the co-implantation parameters that help minimizing said defects lead to increased roughness.

In other words, a compromise has to be made between roughness and formation of these defects, and the recourse to co-implantation thus does not allow as such to satisfactorily solve the above mentioned problems relating to the presence of defects and a superficial roughness.

Embodiments of the present invention seek to overcome these problems. According to a first aspect of the present invention, there is provided a method of forming a structure comprising a taken-off layer from a material chosen from the semiconductor materials from a donor wafer, the method comprising the following successive steps:

(a) implanting atomic species to form a weakness zone in the donor wafer to a depth close to the thickness of the layer to be taken off;

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

(c) supplying energy so as to disunite the taken-off layer from the donor wafer at the weakness zone ;

(d) treating the taken-off layer;

wherein step (d) comprises a recovering operation of the taken-off layer used when the taken-off layer is still in contact with the remaining part of the donor wafer, and wherein the recovering operation is applied by heat treatment at a temperature lower than the re-adhesion temperature of the taken-off layer with the remaining part of the donor wafer.

Other characteristics according to embodiments of the invention are:

- the said re-adhesion temperature is approximately 800°C;
- the step (c) is carried out at a temperature of between 300°C and 550°C;
- the recovering temperature is between 350°C and 800°C;
- the recovering temperature is between 550°C and 800°C;
- the recovering operation is carried out in an inert atmosphere, such as an Ar or N_2 atmosphere ;
- the recovering operation is carried out in an oxidising atmosphere ;
- the recovering operation of step (d) is carried out in continuity with step (c) in a same furnace;
- the recovering operation of step (d) comprises a single change of temperature from the disuniting temperature of step (c) up to the recovering temperature chosen;
- step (c) is carried out at around 500°C for between about 30 minutes and about 2 hours;
- step (a) comprises a simple implantation of hydrogen or helium ;
- step (a) comprises a co-implantation of hydrogen and helium ;
- the recovering operation of step (d) is performed by thermal treatment at a temperature substantially comprised between 575°C and 625°C ;

- the donor wafer comprising a SiGe layer, step (a) is performed by co-implantation under conditions adapted to form the weakness zone within said SiGe layer and for the helium concentration peak to be located, within the thickness of the donor substrate, more in depth than the hydrogen spreading zone and also more in depth than the weakness zone ;
- the recovering thermal treatment is performed for between 30 minutes to four hours ;
- a step permitting the contact to be withdrawn between the taken-off layer and the rest of the donor wafer is carried out after the recovering operation of step (d), possibly followed by a finishing operation, included in step (d), comprising at least one of the following operations: CMP, chemical etching, sacrificial oxidation, heat annealing;
- the taken-off layer is made of $Si_{1-x}Ge_x$ where $0<x\leq 1$;
- the taken-off layer comprises $Si_{1-x}Ge_x$ where $x\neq 0$ and a stop layer for selective etching, and step (d) comprises such selective etching used after the recovering operation and after the contact has been withdrawn with the taken-off layer with the remaining part of the donor wafer;
- the donor wafer comprises a support substrate made of solid Si, a buffer structure made of SiGe and an upper layer comprising $Si_{1-x}Ge_x$ ($x\neq 0$) and the host wafer is made of solid Si;
- the method comprises moreover, prior to step (b), a step for the formation of 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 of the invention, there is provided an application of the method of the first aspect to the formation of a semiconductor on insulator structure.

According to a third aspect of the invention, there is provided a semiconductor on insulator structure obtained after carrying out the recovering operation of the first aspect and after withdrawing the contact of the taken-off layer with the remaining part of the donor wafer, with surface roughness of less than 40 ARMS.

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 represents 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 represents 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 3f represent diagrammatically the different steps of a method of the invention to form a structure comprising a layer taken using Smart-Cut®.

Figure 4 represents a first time evolution of the heat treatment temperatures used during the disuniting step and during the treatment of the taken-off layer according to the method represented by figures 3a to 3f.

Figure 5 represents a second time evolution of the heat treatment temperatures used during the disuniting step and during the treatment of the taken-off layer according to the method represented by figures 3a to 3f.

Figures 6a, 6b and 6c represent cross sectional views obtained by TEM of a Si donor wafer having been subjected to a He/H co-implantation.

Figures 7, 8 and 9 notably present roughness measurements on structures respectively including a taken-off layer comprising Si and SiGe.

Figure 10 notably presents defects quantification results for structures including a taken-off layer comprising respectively Si and SiGe.

A first purpose of the invention is to reduce the duration, economic cost and number of treatment means for a taken-off layer using Smart-Cut®.

A second purpose of the invention is to reduce the quantity of material removed during the treatment of the taken-off layer using Smart-Cut®.

A third purpose of the invention consists of improving the crystalline quality of the taken-off layer with respect to the state of the technique.

A fourth purpose of the invention is to propose a simple method of treating the taken-off layer using Smart-Cut® that is easy to incorporate into the Smart-Cut® taking-off method.

A fifth purpose of the invention is to find a means for using a recovering heat treatment for the taken-off layer both in inert atmosphere and in oxidising atmosphere without however substantially altering the properties of the taken-off layer.

A sixth purpose of the invention is to make semiconductor on insulator structures with high crystalline quality and a working layer thickness that can be very thin.

A seventh purpose of the invention is to make such a semiconductor on insulator structure comprising SiGe or Ge for the semiconductor part.

A eighth purpose of the invention is to determine detachment parameters (implantation, energy) allowing at the same time to reduce the thickness of the defective zone, to limit the presence of defects and to minimize the surface roughness.

We have represented below examples of embodiments of methodes according to the invention, as well as applications according to the invention, based on layers taken off using Smart-Cut® in type IV materials or alloys, and in particular in $Si_{1-x}Ge_x$ where $x \neq 0$.

In reference to figures 3a to 3f, is shown a first method of taking off a layer in $Si_{1-x}Ge_x$ where $x \neq 0$ from a donor wafer to transfer it to a host wafer according to the invention.

In reference to figure 3a, a donor wafer 10, comprising the layer made of $Si_{1-x}Ge_x$ to be taken off (not shown) is illustrated.

Classically, a donor wafer 10 including $Si_{1-x}Ge_x$ comprises a solid Si substrate on which has been formed a buffer structure in SiGe (not shown) made up of different layers, such that the latter has a gradual evolution in thickness of its composition in Ge, starting from 0% at the solid Si substrate level to around 100x% at the level of the interface with the upper layer made of $Si_{1-x}Ge_x$.

Of course the donor wafer 10 may have any other configurations for which a layer in $Si_{1-x}Ge_x$ either relaxed or not is present in its upper part.

Optionally, a layer of strained Si is formed by crystalline growth (for example CVD) on the $Si_{1-x}Ge_x$ layer.

In reference to figure 3b, a weakness zone 4 is then formed in the donor wafer 10 at the level of its upper part made of $Si_{1-x}Ge_x$.

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

The implantation of atomic species may be a simple implantation (i.e. an implantation of, principally, a single atomic type) such as for example an implantation of hydrogen, helium or rare gases.

The implantation of atomic species may be a co-implantation of atomic species (i.e. an implantation of, principally, two atomic species) such as for example an implantation of hydrogen followed by an implantation of helium (and reciprocally).

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

The depth of the implantation is chosen so that it is close to or greater than the desired thickness of the layer to be taken off 1.

Thus for a single implantation with hydrogen at approximately $6.10^{16}/cm^2$ and energy of between 20 and 60 keV, we can obtain a depth of implantation of around 300 to 600 nanometres.

Thus for a co-implantation with helium of around $0.9.10^{16}/cm^2$ and energy of between 50 and 90 keV and hydrogen at $10^{16}/cm^2$ and energy of between 20 and 60 keV, we can obtain a depth of implantation of around 300 to 600 nanometres.

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.

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 solid Si.

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 of this or these bonding layer(s) being made of SiO_2, they may be formed by thermal oxidation or SiO_2 deposit.

The thermal oxidation of the host wafer 20 is usually preferred as it uses in most cases Si oxidation.

The thermal oxidation of the donor wafer 10 may be carried out at the level of the layer to be taken off 1 of $Si_{1-x}Ge_x$.

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

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

Secondly, and in particular in the case of one or more bonding layers being positioned between the donor wafer 10 and the host wafer 20, a heat treatment may possibly be carried out after the recovering operation discussed below, to further strengthen the bonding, and in particular by creating covalent links.

Information on the bonding techniques that may used within the scope of the invention may be found in particular in the document "Semiconductor Wafer Bonding Science and Technology" (QY Tong and U. Gösele, Wiley Interscience Publication, Johnson Wiley and Sons, Inc.).

In reference to figures 3d and 3e, are described the respective disuniting and recovering steps of the taken-off layer 1.

In reference to figure 3d, is described the disuniting step. This is carried out by providing heat energy and/or mechanical energy, sufficient to break weak links at the weakness zone 4, and thus disunite the taken-off layer 1 from the rest of the donor wafer 10'. The bringing of heat energy is for instance then sufficient to cause, at the weakness zone 4 level, thermal effects on the gaseous species enclosed there causing the rupture of weak links, without any mechanical intervention being required.

Disuniting may be obtained at temperatures of between around 300°C and around 550°C for durations of varying lengths which depend on whether the temperature is lower (longer) or higher (shorter). We can use, for example, for a layer to be taken off made from $Si_{1-x}Ge_x$, heat treatment at a temperature of around 500°C for a duration that can range from 15 to 30 minutes up to 2 hours.

Such disuniting of the taken-off layer 1 from the rest of the donor wafer 10', when carried out using only heat, will then permit the taken-off layer 1 to be disunited without breaking the contact with the rest of the donor wafer 10' (see figure 3d for illustration).

It is then possible to carry out the recovering heat treatment directly after the disuniting, without necessarily removing the wafers from the furnace (in which the disuniting heat treatment method took place), and without the need for any additional handling.

Moreover, the remaining part of the donor wafer 10' offers protection to the taken-off layer 1 against any possible contaminants, oxidants or other such agents, which offers the possibility of again using the heat treatment in various atmospheres.

In this way, within the scope of the method of the invention, and in reference to figure 3e, a recovering operation is carried out by heat treatment at a temperature T_2 chosen below the re-adhesion temperature from which the taken-off layer 1 re-adheres (or joins together again) with the remaining part of the donor wafer 10'.

Advantageously, the re-adhesion temperature is here considered, within the scope of the invention, and based on the experience of the applicant, as equal to approximately 800°C.

This recovering heat treatment on the taken-off layer 1 is carried out in an inert atmosphere (such as an Ar or N_2 atmosphere) that is oxidising or slightly oxidising.

Optionally, the temperature T_2 is greater than the temperature T_1 to which the wafers 10 and 20 were subjected when disunited.

The temperature T_2 may for example be situated between 350°C and 800°C, maintained during 30 minutes to 4 hours.

The temperature T_2 may more particularly be situated between 550°C and 800°C.

In reference to figures 4 and 5, are provided examples of possible temperature evolutions according to the invention during joining phases and recovering of the taken-off layer 1.

Thus, in reference to figure 4, a first platform of around 500°C is reached and maintained for around 30 minutes in order to create at the end a disuniting (at the level of the arrow 1000), then an increase in temperature to approximately 600°C to carry out a recovering operation according to the invention (at the level of the temperature platform 2000). This recovering operation may then last for between 30 minutes and 2 hours.

The recovering temperature may thus be for instance held for between 30 and 60 minutes.

In reference to figure 5, the disuniting does not occur during a temperature platform but during a temperature increase (for instance at a temperature around 500°C, at the level of the arrow 1000 in the figure) then the recovering operation temperature platform 2000 is reached at around 600°C.

Surprisingly, the applicant has thus observed that by using such a recovering operation step on the taken-off layer 1, the latter then had:

- an improved crystalline quality in its 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);

In reference to figure 3f, the contact between the remaining part of the donor wafer 10' and the recovered taken-off layer 1' is removed, to obtain finally a structure 30, comprising a taken-off layer and recovered 1' made of $Si_{1-x}Ge_x$ and the host wafer 20. This structure 30 has an improved crystalline quality and reduced roughness, without having need for an sacrificial oxidation operation and without any significant loss of part of the taken-off layer 1.

Finishing steps may then be possibly used to remove any slight roughness and the few remaining crystalline defects at the surface of the taken-off layer 1', such as the use of CMP, polishing or chemical etching.

Optionally, a layer of Si may be added by epitaxy onto the $Si_{1-x}Ge_x$ layer so that it is elastically strained.

In one particular embodiment of the invention, a layer of strained Si was formed prior to it being taken off from the $Si_{1-x}Ge_x$ layer. The structure 30 then comprises in this case a taken-off layer 1 having a layer of strained Si on which lies a layer of $Si_{1-x}Ge_x$.

The layer of $Si_{1-x}Ge_x$ may possibly be removed (for example by selective etching by using for example $HF:H_2O_2:CH_3COOH$, in order to obtain finally a final sSOI structure.

In another specific embodiment of the invention, where the taken-off layer in $Si_{1-x}Ge_x$ comprises one or more stop layers, such as a layer in $Si_{1-x}Ge_y$ where $y \in [0;1]$ and $y \neq x$ (formed in the layer to be taken off, prior to takting-off), we can advantageously carry out at least one selective etching (combined with polishing or not) by using known solutions and permitting a particularly effective finishing step to be carried out, as for instance notably taught in the documents FR 2,842,349 and FR 2,842,350.

This layer of $Si_{1-x}Ge_y$ may for example be Si elastically strained by the neighbouring $Si_{1-x}Ge_x$ (where y = 0).

In fact, with the previous recovering operation considerably reducing the surface roughness and the non-uniformities of thickness in the taken-off layer 1, it is then possible to use selective etching that is more or less identical to those of the state of the technique, but by also eliminating the disadvantages that they may present (described previously in this document).

In reference to figure 2, a structure 30 SiGeOI of 20% Ge (photographed by TEM) obtained by the applicant following a post-disuniting recovering heat treatment transfer at 600°C, shows a recovered taken-off layer 1' (covering a layer of SiO_2 5) that comprises very few crystalline defects and very little roughness with respect to the semiconductor on insulator structure of figure 1.

In particular, it can be noted the disproportion between the thickness of the defective zone 1A of the taken-off layer 1 in reference to figure 1 and that of the remedied taken-off layer 1' in reference to figure 2.

Similarly, and for a same thickness of taken-off layers 1 for figure 1 and for figure 2, the sound zone 1B is much greater proportionally in the SGOI obtained according to the invention than in the semiconductor on insulator according to the state of the technique.

It has to be noted that the decrease of the thickness of the defective zone 1A is more particularly observed when the weakness zone is formed by co-implantation of atomic species.

This is principally due to the fact, already mentioned above, that the total dose of co-implanted species is definitely lower than the dose to be implanted when a single species is implanted.

Hence co-implantation has the advantage, when compared to the implantation of a single species, to decrease the thickness of the defective zone, which notably allows for reducing or simplifying the finishing treatments performed after detachment.

Results of surface roughness measurements made on such a SGOI structure with 20% Ge, carried out by the applicant, are presented in the

table below. These measurements were made just after disuniting at 500°C for 30 minutes following simple implantations or co-implantations, and recovering treatment at 500°C or 600°C.

The roughness was measured with an Atomic Force Microscope (AFM) sweeping 10×10 μm ² surface areas, and are given in RMS or peak to valley (PV) values.

It should be noted that the applicant has carried out a sufficient number of measurements to validate the results.

Nature of the implantation	Bonding strengthening treatment	Surface roughness	
		RMS (Å)	PV (Å)
Simple implantation H: 40keV-6.10^{16}/cm²	500°C/30 min.	80 – 85	850
	600°C/30 min	38	420
Co- implantation of H and He: H: 35keV-1.0.10^{16}/cm² He: 70keV-0.9.10^{16}/cm²	500°C/30 min.	49	407
	600°C/30 min.	33	272

In this table, it can be noted that, in all the cases (implantation of a single species, co-implantation of several species), a recovering treatment at 600°C reduces by almost a third both the mean (RMS) and maximum (PV) roughnesses with respect to a recovering treatment carried out at the disuniting temperature (approximately 500°C), following a single species implantation, the roughnesses being less than 40 Å RMS, and even less than 35 Å RMS for co-implantation cases, and below 275 Å PV.

The applicant has thus established that there is significantly less roughness when the taken-off layer 1 has undergone a recovering treatment.

In this table, it may also be observed that there is less roughness in the case of a co-implantation than in the case of a single implantation.

Other roughness measurements on a sSI structure (for which a strained Si layer has been deposited on a SiGe layer comprising 20% of Ge) made by the Applicant are presented hereafter. These results more particularly concern certain detachment parameters, and notably several co-implantation parameters.

One reminds hereunder the different problems encountered when forming a structure comprising a Si layer taken off from a donor wafer according to a taken off process of the Smart-Cut®type. These problems have been discussed in the Applicant's PCT application already mentioned above, and which teaching have been made available to the public on March, 1 2005 under reference IPCOM000083333D.

The recourse to a co-implantation can indeed lead to the formation of blisters at the bonding interface and of defects within the thickness of the taken off layer.

Particles or organic substances present on one and/or the other of the wafers to be bonded can prevent the bonding to be carried out in a satisfying manner at certain regions of the bonding interface. The implanted species may then diffuse to the weakly bonded bonding interface regions, forming blisters at the level of the bonding interface.

Furthermore, locally, the bonding energy may not be sufficient to allow the detachment of the donor wafer. Certain zones of the taken off layer may then not be transferred onto the host wafer (these zones are communally designated under the term of "non transferred zones" or ZNT).

In addition, crystalline defects of the nano-cavities type (presenting a diameter of some nanometers) may be observed, depending upon the chosen co-implantation conditions, within the thickness of the taken off layer, beyond the defective zone. These defects may result from an agglomeration of Silicium or Germanium atoms displaced during implantation. In particular, when helium is implanted sensibly at the same depth than hydrogen, these nano-cavities type defects (located beyond the defective zone, but as much

undesirable than the defects present in the defective zone) are observed within the thickness of the taken off layer. The appearance of these defects necessitates the removal after detachment of a thickness of material more important than necessary, and thus necessitates the taking off of a thicker layer.

In reference to the views of figures 6a, 6b et 6c obtained by TEM, a co-implantation of helium and hydrogen in a Si donor wafer for the taken off of a layer following a thermal detachment treatment is represented.

Figure 6a represents a view obtained by TEM pthotography of a Si donor wafer having been subjected (see arrows) to a co-implantation of helium and hydrogen. The distribution of these species in the thickness of the donor wafer is perceptible (see dark points) on this figure 6a.

After bonding to a host wafer, a thermal treatment leads to the disunion at the level of the weakness zone (see figure 6b). Figure 6c represents (in reversed sight compared to figure 2) the taken-off layer after detachment and transfer onto a host wafer. On this figure 6c, one can notice the defective zone close to the surface, as well as the presence of defects (da rk points) in the thickness of the taken-off layer.

Each of the implanted species is distributed, within the thickness of the donor wafer, according to a repartition profile having a spreading zone within which the species is mainly concentrated and presenting a maximum concentration peak.

More precisely, the repartition has a quasi-Gaussian profile presenting a standard deviation (defining said spreading zone wherein the species is mainly distributed, for instance within which one finds 70% of the implanted species) and a maximum concentration peak which notably depend upon the implantation energy.

The helium atoms diffuse within the Si matrix more easily than the hydrogen atoms. Hence if helium is implanted close to the bonding interface, the risk increases that blisters or crystalline defects beyond the defective zone form. A way to cure this problem consists in implanting helium more in

depth than hydrogen, so that the hydrogen containing region may block the diffusion of helium.

It is more precisely a question of controlling the co-implantation parameters so that the helium peak is located more in depth than the hydrogen spreading zone.

However, it has been shown that the roughness after detachment does not follow the same tendency, and tends to increase when helium is implanted more deeply than hydrogen. This signifies that the implantation conditions (i.e. implantation doses and energies) do not allow to independently controlling the roughness and the formation of blisters and crystalline defects beyond the defective zone. It is thus necessary to make a compromise between the best parameters for limitation of the formation of blisters and defects and the best parameters for limitation of the surface roughness.

A solution making it possible to overcome this problem has already proposed by the Applicant in PCT application already mentioned previously and which teaching was made available to the public on March 1, 2005. Generally speaking, this solution consists in precisely controlling the relative position of the hydrogen and helium peaks in the implanted donor wafer (the helium peak being located at the level of the embrittlement zone and more in-depth than the hydrogen spreading zone), and in jointly controlling the dose of each species (the helium dose accounting for approximately 40% to 60% of the total amount). By carrying out the step of implantation by co-implanting according to these parameters, a satisfactory compromise can be found between roughness and formation of defects.

The experiments carried out by the Applicant on the detachment at the level of layers containing Ge (typically layers of SiGe comprising more than 15% Ge) led to surprising results with regard to the roughness and the formation of blisters and crystalline defects beyond the defective zone.

A possible embodiment of the process according to the present invention is as follows:

- to carry out a co-implantation, typically of helium and hydrogen, in a layer of SiGe, according to implantation parameters adapted to shift the concentration peaks of helium and hydrogen, in particular so that the helium peak is located more in-depth than the hydrogen spreading zone, but also so that the helium peak is located more in-depth than the embrittlement zone

- and to implement a post disunion recovering heat treatment at a temperature about 600°C (+/- 25 °C), to be maintained from 30 minutes up to four hours, for example during approximately an hour.

Typically, the implantation parameters are adapted "to place" the helium peak at a depth approximately 1,2 times higher than the depth of the hydrogen peak. As an example, for the conditions of implantation dose and energy presented in the present application, this means placing the helium peak at more than 500 angströms from the hydrogen peak.

The helium dose lies between 30% and 70% of the total dose (hydrogen + helium), preferably ranging between 40% and 60% of the total dose. The total dose typically represents some 10^{16}atomes/cm², without that being restrictive.

Such an embodiment makes it possible to strongly reduce roughnesses (in particular those of high frequencies), and makes in addition low roughnesses independent from the helium implantation depth. It is thus possible, within the framework of this embodiment, to implant helium more deeply than hydrogen, which makes it possible to limit the formation of blisters and crystalline defects beyond the defective zone in the taken-off layer, the diffusion of helium in the transferred layer being blocked by the hydrogen spreading zone.

Consequently, this embodiment makes it possible to minimize at the same time the roughness post detachment, the number of defects of the blisters type and the number of defects found in the thickness of the taken-off layer. This results in authorizing the taking off of a lower total thickness, which makes it possible to reduce, or all at least to simplify, the post-detachment finishing operations (polishing, selective etching, sacrificial

oxidation, etc). In particular, it is then possible, in order to form a structure including a taken-off layer of 500 angströms thick, to only take off a thickness of 1500 angströms, and consequently to reduce the thickness of the zone to be removed to approximately 1000 angströms.

Figures 7 to 9 represent measurements of roughness post-detachment on a SOI structure and a SGOI structure (at 20% of Ge). These measurements were carried out just after disunion following simple implantations of hydrogen only (indicated by Honly on these figures) or He/H co-implantations (indicated by CoI on these figures), and a recovering treatment of one hour, at 500°C or 600°C.

More precisely, the change of the temperature at the time of the operations of disunion and recovering was as follows: maintenance of a stage at 350°C during approximately an hour, then rise in temperature according to a slope of 5°C/mn, then maintenance of a stage (to carry out the recovering operation) respectively at 500°C and 600°C during approximately an hour.

Figures 7 and 8 thus represent measurements of roughness at high frequencies carried out by sweeping respectively a surface area of 2*2µm² and a surface area of 10*10µm² using a AFM microscope. Figure 9 represents measurements of roughness at low frequencies carried out by profilometry using the Dektak® tool of Veeco Instruments Inc company.

On each one of these figures 7 to 9, one has represented results of roughness measurement expressed on the left in average values (RMS) and on the right in maximum values (statement).

On these figures, one has showed the result of measurement carried out following implantation in a layer of Si, and in a layer of SiGe (see figure 7 on which columns relative respectively to Si and in SiGe are clearly distinguished).

As concerns Si, two wafers, subjected to a He/H co-implantation, were studied. The co-implantation parameters were as follows:

H: 30kev-1.10^{16}/cm²

He: 52 or 60 keV - 1.010^{16}/cm²

As concerns SiGe, five wafers were studied, namely a wafer subjected to an implantation of H only (H: 30 keV, $6.10^{16}/cm^2$), and four others subjected to a He/H co-implantation according to the following parameters:

H: 30 keV - $1.10^{16}/cm^2$

He: 48, 52, 56 or 60 keV - $1.10^{16}/cm^2$

Figure 7 confirms the very interesting profit in term of high frequencies roughnesses related to the He/H co-implantation in comparison with H alone (and that that it is following a recovering treatment at 500°C or at 600°C).

It is observed however that for a high temperature treatment at 600°C, roughness strongly decreases (typically of more than half) for all the alternatives, including implantation of H alone. And these values of roughness are even weaker when a co-implantation is carried out.

In addition, one observes, that for a 500°C treatment (in a way similar to what was observed in Si) roughness tends to increase when the helium peak is located more in-depth than the embrittlement zone (typically here for helium implantation energies higher than 56 keV).

On the other hand, within the framework of a high temperature treatment at 600°C, roughness is sensibly not modified when one implants helium more deeply than the embrittlement zone. One observes here an unexpected behaviour, in opposition against what was observed in Silicon, as well as in SiGe with a 500°C treatment.

The results presented on figures 8 and 9 confirm these observations.

The behavior in co-implantation, during a treatment at 600°C, is surprising insofar as the phenomenon noted up to now by the Applicant within the framework of a detachment on the level of a layer of Si were that of an increase in roughness when the helium implantation energy was increased (helium peak shifted more in-depth than the embrittlement zone).

In reference to figure 10, the Applicant also carried out measurements aiming at noting the number of defects (ZNT type, blisters) present in the various transferred layers.

The macroscopic observation (in grazing light) makes it possible to detect the defects of the ZNT type or blisters. One regards here the sum of

these defects (ZNT + blisters) as being representative of the specific defects related to the implantation and observed post-detachment.

A significant number of defects is noted in the two alternatives He: 48keV and He:52keV, i.e. the alternatives for which the helium distribution profile is superimposed or quasi superimposed with the hydrogen profile (the helium peak being then "inside" the hydrogen spreading zone).

On the other hand, a low number of defects is noted in the alternatives He: 56 keV and He: 60 keV, i.e. the alternatives for which the helium peak is located more in-depth than the hydrogen spreading zone. In other words, the defects of the blisters type are minimized when helium is deeply implanted (and that, in the case of a recovering operation at 600°C, without roughness being increased).

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

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 comprising a taken-off layer chosen among the semiconductor materials from a donor wafer, the method comprising the following successive steps:

(a) implanting atomic species to form a weakness zone in the donor wafer to a depth close to the thickness of the layer to be taken off;

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

(c) supplying energy so as to disunite the taken-off layer from the donor wafer at the weakness zone;

(d) treating the taken-off layer;

wherein step (d) comprises a recovering operation of the taken-off layer used while the taken-off layer is still in contact with the remaining part of the donor wafer and wherein the recovering operation is applied by heat treatment at a temperature lower than the re-adhesion temperature of the taken-off layer with the remaining part of the donor wafer.

2. Method according to claim 1, wherein the said re-adhesion temperature is around 800°C.

3. Method according to any one of the preceding claims, wherein step (c) is performed at a temperature comprised between 300°C and 550°C.

4. Method according to any one of the previous claims, wherein the recovering temperature is between 350°C and 800°C.

5. Method according to any one of the previous claims, wherein the recovering temperature is between 550°C and 800°C.

6. Method according to any one of the previous claims, wherein the recovering operation is carried out in an inert atmosphere, such as an Ar or N_2 atmosphere.

7. Method according to any one of claims 1 to 5, wherein the recovering operation is carried out in an oxidising atmosphere.

8. Method according to any one of the previous claims, wherein the recovering operation of step (d) is carried out in continuity from step (c) in a same furnace.

9. Method according to the previous claim, wherein the recovering operation of step (d) comprises a single temperature change as from the disuniting temperature of step (c) to the temperature chosen for the recovering.

10. Method according to the previous claim, wherein step (c) is carried out at around 500°C for a duration that can last up from 30 minutes to around 2 hours.

11. Method according to any one of the previous claims, wherein step (a) comprises a simple implantation of hydrogen or helium.

12. Method according to any one of claims 1 to 11, wherein step (a) comprises a co-implantation of hydrogen and helium.

13. Method according to any one of the preceding claims, wherein the recovering operation of step (d) is carried out by thermal treatment at a temperature substantially comprised between 575°C and 625°C.

14. Method according to claim 12 and claim 13, wherein the donor wafer comprises a SiGe layer, and wherein step(a) is carried out according to implantation parameters adapted to form the embrittlement zone in said SiGe layer, and for the helium concentration peak to be located, in the thickness of the donor wafer, more in-depth than the hydrogen spreading zone and more in-depth than the embrittlement zone.

15. Method according to any one of the preceding claims, wherein the recovering heat treatment is implemented for one length of time ranging between 30 minutes and four hours.

16. Method according to any one of the preceding claims, wherein a step making it possible to withdraw the contact of the taken off layer from the remainder of the donor wafer is implemented after the recovering operation of step (d).

17. Method according to the preceding claim, wherein, after having withdrawn the contact of the taken off layer from the remainder of the donor wafer, step (d) further comprises at least one of the following operations: CMP, chemical etching, sacrificial oxidation, thermal annealing.

18. Method according to any one of the preceding claims, wherein the taken-off layer is in $Si_{1-x}Ge_x$, with $0 < x \leq 1$.

19. Method according to any one of claims 1 to 17, wherein the taken-off layer is in strained Si and in $Si_{1-x}Ge_x$ with $0 < x \leq 1$.

20. Method according to the preceding claim, wherein the $Si_{1-x}Ge_x$ layer is, after step (d), selectively etched with respect to the layer of strained Si.

21. Method according to any one of the preceding claims, wherein the taken-off layer comprises $Si_{1-x}Ge_x$, with $x \neq 0$, and a barrier layer to selective etching, and in that step (d) comprises such a selective etching implemented subsequently to the recovering operation, and after having withdrawn the contact of the taken off layer from the remaining part of the donor wafer.

22. Method according to any one of the preceding claims, wherein the donor wafer comprises a bulk Si support substrate, a buffer structure in SiGe, and a top layer comprising $Si_{1-x}Ge_x$ ($x \neq 0$), and wherein what the host wafer is in bulk Si.

23. Method according to any one of the previous claims, wherein it comprises moreover, prior to step (b), a step for forming a bonding layer on the donor wafer and/or on the host wafer, the bonding layer being made of an electrically insulating material, such as for example SiO_2, Si_3N_4 or $Si_xO_yN_z$.

24. Application of the method of the previous claim to the formation of a semiconductor on insulator structure.

25. Semiconductor on insulator structure obtained after carrying out the recovering operation of step (d) of the method according to any one of claims 1 to 23, and after withdrawing the contact of the taken-off layer with the remaining part of the donor wafer, with surface roughness of less than 40 ARMS.

ABSTRACT

The invention relates to a method of forming a structure comprising a layer chosen among semiconductor materials from a donor wafer, the method comprising the following steps:

(a) implanting atomic species to form a weakness zone in the donor wafer to a depth close to the thickness of the layer to be removed;

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

(c) supplying energy so as to disunite the taken-off layer from the donor wafer at the weakness zone;

(d) treating the taken-off layer;

wherein step (d) comprises a recovering operation of the taken-off layer carried out when the taken-off layer is still in contact with the remaining part of the donor wafer, and in that the recovering operation is applied by means of heat treatment at a temperature lower than the re-adhesion temperature of the taken-off layer with the remaining part of the donor wafer.

FIGURE 3d