A METHOD OF FABRICATING A THIN FILM

Technical field and prior art

The present invention relates to a method of fabricating a thin film of semiconductor material involving the Smart Cut™ technique. An example of the use of the Smart Cut™ technique has been described in United States patent document US-A-5 374 564 or in the article by A.J. Auberton-Hervé et al, entitled "Why can Smart Cut change the future of microelectronics?", Int. Journal of High Speed Electronics and Systems, Vol. 10, No. 1, 2000, pp. 131-146. This technique employs the following steps:

a) bombarding one face of a substrate (for example formed from silicon) with hydrogen or rare gas type light ions (for example helium) to implant said ions in a sufficient concentration into the substrate and create a layer of weakening microcavities;

b) bringing said face of the substrate into intimate contact with a stiffener or receiving substrate; and

c) fracturing/splitting at the layer of microcavities by applying a heat treatment and/or mechanical detachment stress, such as inserting a blade at the level of the layer of microcavities and/or applying tensile and/or bending and/or shear stresses, and/or applying ultrasound or microwaves of suitable power and frequency.

By detaching a portion of the implanted substrate, that method can produce a thin film with a homogeneous thickness substantially corresponding to the distance between the face of the bombarded substrate and the layer of microcavities formed by implantation. Compared with other known methods of fabricating thin films, such as the method known as "SIMOX" (described in the document "SIMOX SOI for integrated circuit fabrication", Hon Wai Lam, IEEE Circuits and Devices Magazine, July 1987) or methods of thinning a wafer by chemical or any other

chemical-mechanical abrasion, that method does not require very high implantation doses, nor an etch-stop barrier.

However, with that method, the bulk of the transferred thin film contains a simple metal (Al), transition metals (Ti, Cr, Fe, Co, Ni, Cu, Zn, etc), alkali metals (Li, Na, K etc), alkaline-earth metals (Mg, Ca, Ba, etc), halogen (F, Br, Cl), metalloid (As), or organic types of contaminants (C, N, O) as contaminating impurities. Those impurities correspond to impurities present in the starting substrate and/or impurities introduced by the method employed. As an example, the presence of transition metal type impurities may cause large variations in the electrical properties in the transferred thin film.

Summary of the invention

The invention aims to overcome the disadvantages mentioned above and proposes a solution which allows the production of thin films by a method comprising a step of implanting light ions to create a layer of microcavities corresponding to a zone of weakness at which the substrate can be split (Smart Cut™ technique), while reducing the bulk concentration of impurities present in the detached film.

This aim is achieved by means of a method of fabricating a thin film, comprising:

a) at least one step of implantation by bombarding one face of a substrate formed from a semiconductor material with light ions of the hydrogen or helium type, alone or in combination with other species (for example by boron-hydrogen co-implantation) to form, at a predetermined depth in the substrate, a layer in which said implanted ions are concentrated, said concentrated layer defining a thin film in the upper portion of the substrate;

b) a step of bringing the face of the substrate into intimate contact with a stiffener;

c) a step of detaching the thin film in contact with the stiffener by splitting at the concentrated layer of ions;

in which method, after implantation step a) and before detachment step c), a heat treatment step is carried out to trap contaminants in the concentrated layer of implanted ions, said treatment not causing splitting of the substrate at the concentrated layer of implanted ions. After step c), the zone perturbed by trapping the contaminants and by the detachment step is eliminated.

The heat treatment step carried out after implantation firstly allows the development/formation of microcavities at the concentrated layer of implanted ions which form trapping cavities and secondly, allows diffusion and trapping of the contaminants in said cavities. The portion of the substrate located above the trapping microcavities, which corresponds to the thin film to be transferred, thus has a reduced concentration of contaminating species except at the surface. Chemical-mechanical polishing and/or appropriate selective chemical attack can eliminate the surface zone which has been perturbed and contaminated by trapping of the contaminants and by the detachment step. As a result, the method of the invention allows the production of thin films having a reduced concentration of contaminating species.

The substrate may be a substrate of silicon, germanium, silicon-germanium, gallium nitride, gallium arsenide or silicon carbide.

In one aspect of the invention, the method also comprises an additional implantation step consisting of bombarding the face of the substrate under implantation conditions which are different from those used for the implantation of step a), said additional implantation

step being carried out at an implantation energy which is greater than that of step a) to create a concentrated layer of additional ions at a greater depth than the concentrated layer of ions created during step a).

In this case, the trapping cavities are developed/formed in the concentrated layer of additional ions which is located below the concentrated layer of ions which is intended to form a plane of weakness along which the thin film is to be detached. The contaminants are then trapped in a zone located below the thin film detachment zone and are confined in the bulk of the substrate which does not form part of the thin film to be transferred.

The additional implantation step may be carried out with helium gas ions.

In step c), detachment of the thin film (substrate fracture) may be brought about by a detachment stress applied at the concentrated layer of implanted ions. The detachment stress may consist of applying a heat treatment (an anneal carried out at a temperature which is higher than the temperature of the trapping heat treatment) and/or a detachment mechanical stress such as insertion of a blade at the concentrated layer of implanted ions, and/or the application of tensile stresses and/or the application of ultrasound or microwaves with a suitable power and frequency.

Brief description of the drawings

· Figures 1A to 1E are diagrammatic sectional views showing the production of a thin film of Si in accordance with one implementation of the invention;

· Figure 2 is a flow-chart showing the steps carried out in Figures 1A to 1E;

· Figures 3A to 3F are diagrammatic sectional views showing the production of a thin film of Si in accordance with another implementation of the invention;

· Figure 4 is a flow-chart of the steps carried out in Figures 3A to 3F;

· Figure 5 shows the fluorine concentration in a Si substrate as a function of the duration of the contaminant trapping heat treatment of the invention;

· Figure 6 shows the concentration of fluorine in a Si substrate as a function of the duration of the contaminant trapping heat treatment of the invention; and

· Figure 7 shows the influence of the trapping heat treatment of the invention on contaminants of various natures.

Detailed description of implementations of the invention

The method of the present invention is applicable in general to the fabrication of thin films of semiconductor materials from any type of substrate compatible with the Smart Cut™ technique. Such substrates are in particular substrates of silicon (Si), germanium (Ge), silicon-germanium (SiGe), gallium nitride (GaN), gallium arsenide (GaAs), silicon carbide (SiC), etc.

The invention proposes applying, during the fabrication of a thin film using the Smart Cut™ technique, an additional heat treatment step, after the implantation step and before the detachment step, which additional step serves to form microcavities at the implanted layer in which the contaminants present in the starting substrate and/or introduced during the implantation and bonding steps are trapped. Said microcavities have incomplete chemical bonds on their internal walls which can trap atoms of contaminating species.

This additional heat treatment must be carried out at a temperature sufficiently high to allow the contaminating species to diffuse into the trapping microcavities but without exceeding the limiting temperature which causes fracture of the substrate at the implantation layer by a crystal rearrangement effect in

the substrate and pressure in the microcavities. The trapping microcavities may have developed and/or been formed directly in the implantation layer intended to cause splitting of the substrate (Smart Cut™ technique) or in a separate implantation layer formed beneath said layer.

The documents "Comparison of Cu gettering to H^+ and He^+ implantation-induced cavities in separation-by-implantation-of-oxygen wafers by M. Zhang et al, Journal of Applied Physics, Vol 85, n° 1, January 1, 1999, and "Gettering of platinum and silver to cavities formed by hydrogen implantation in silicon" by A. Kinomura et al, Nuclear Instruments and Methods in Physics Research B 127/128 (1997), 297-300, disclose the formation of trapping cavities by H^+ or He implantation followed by heat treatment. However, the trapping cavities are not used to fracture/split the substrate. In contrast, in those two documents, the contaminants are deliberately introduced by ion implantation and are conserved in the substrate.

A method of producing a thin film in accordance with one implementation of the invention is described below with reference to Figures 1A to 1E and 2.

In this implementation, the starting substrate or donor substrate 1 is constituted by a wafer of monocrystalline silicon covered with a layer 2 of silicon oxide (SiO_2) obtained by thermal oxidation and having a thickness of about 1450 Å [Angstroms].

In a first implantation step (step S1), the substrate 1 undergoes ionic bombardment 10 of hydrogen ions H^+ through the flat face 7 of the substrate comprising the (SiO_2) layer 2. Implantation of H^+ ions is carried out at an implantation energy of about 37 keV [kiloelectron volts] and at an implantation dose of about 5.75×10^{16} atoms/cm^2 [atoms/square centimeter]. These implantation conditions allow a concentrated layer 3 of ions to be created parallel to the face 7 of the

substrate at a predetermined depth in the substrate 1, defining a thin film 4 in the upper region of the substrate 1 and a portion 5 in the lower region of the substrate corresponding to the remainder of the substrate 1 (Figure 1A).

The implantation dose is selected so that the concentration of H^+ ions in the layer 3 is sufficient to create a layer of microcavities directly after implantation or during a subsequent heat treatment step. However, it should be noted that microcavities may already have formed during implantation. The depth of penetration of the H^+ ions into the substrate is principally determined by the implantation energy level. In the example described here, implantation is carried out at an implantation energy of about 37 keV, which allows the concentrated layer 3 of H^+ ions to be formed about 300 nm [nanometers] beneath the face 7 of the bombarded substrate 1.

The implanted starting substrate 1 is then bonded, for example by molecular bonding, to a stiffener 6, for example a wafer of silicon (step S2, Figure 1B). The starting substrate 1 contains residual impurities (such as fluorine F, carbon C, etc). Furthermore, the steps of oxidation (formation of SiO_2 layer), ion implantation and bonding may increase the amount of contamination by impurities in the starting substrate 1.

In accordance with the invention, a suitable heat treatment step is carried out which allows the development and/or formation of microcavities in the concentrated layer 3 of H^+ ions and diffusion of various contaminating species to the microcavities where they are trapped (step S3, Figure 1C). In this implementation, the microcavities not only constitute traps for the diffused contaminating species, but also a plane of weakness allowing subsequent fracture of the substrate by applying mechanical stresses.

The heat treatment step may, for example, be an anneal at 350°C for a period of 18 h [hours]. Such an anneal can locally increase the quantity of fluorine ions at layer 3 by a factor of 50 and, as a result, reduce the concentration of fluorine ions in the remainder of the substrate and in particular in the portion corresponding to the thin film 4 to be detached. The 350°C anneal for 18 h can also halve the concentration of carbon impurities in the thin film 4. Finally, said (350°C - 18 h) anneal causes the formation of microcavities which locally weaken the substrate and endow this region (i.e. at layer 3) with density, dimensional, distributional, morphological etc characteristics which are compatible with a fracture.

In the example described here, the heat treatment step is carried out after the step of bonding onto the stiffener (step S2). However, this heat treatment step may be carried out before the step of bonding onto the stiffener 6.

After the heat treatment step, a thin film 4 is detached from the substrate 1 by splitting (step S4, Figure 1D). This step is, for example, carried out by applying mechanical stresses, such as by inserting a blade at the microcavity zone, causing a fracture to propagate along said zone.

The thin film 4 transferred onto the stiffener 6 contains few contaminants in its bulk apart from at its fractured surface 8 which, after the heat treatment step, concentrates the contaminating species which have diffused and which are trapped in the microcavities.

A conventional polishing step (chemical-mechanical polishing) is then carried out to eliminate the perturbed contaminated zone of the surface 8 and to reduce its roughness (step S5, Figure 1E). The thickness withdrawn by polishing is of the order of 1500 Å. The contaminated/perturbed zone may also be eliminated by

selective chemical attack (etching) optionally followed by polishing to improve the surface roughness.

A final high temperature heat treatment (1100°C) may then be applied to consolidate the structure and repair any defects present in the transferred film (step S6).

Figures 3A to 3F and 4 illustrate a variation of a method of producing a thin film in accordance with the invention. This implementation differs from that described above in that two layers of microcavities are formed in the substrate at different depths, one layer being used to trap the contaminants and the other to allow the thin film to be detached.

The starting substrate 10 is constituted by a wafer of monocrystalline silicon covered with a layer 11 of silicon oxide (SiO_2) obtained by thermal oxidation and having a thickness of about 1450 Å.

In a first implantation step (step S10), the substrate 1 is firstly subjected to ionic bombardment 20 of helium ions He through the flat face 13 of the substrate comprising the (SiO_2) layer 11. He ion implantation is carried out at an implantation energy of about 60 keV and an implantation dose of about 1.5×10^{16} atoms/cm^2. These implantation conditions allow a concentrated layer of He ions 12 to be created in the substrate 10 at a depth of about 300 nm (Figure 3A).

In a second implantation step (step S11), which may be before or after the first He ion implantation step, the substrate 1 undergoes ionic bombardment 21 of hydrogen ions H^+ through the flat face 13. H^+ ion implantation is carried out at an implantation energy of about 32 keV and an implantation dose of about 1.5×10^{16} atoms/cm^2. These implantation conditions allow a concentrated layer 14 of H^+ ions to be created at a depth of about 230 nm in the substrate 10, defining a thin layer 15 in the upper region of the substrate 10 and a portion 16 in the lower region of the substrate

corresponding to the remainder of the substrate 10 (Figure 3B).

In the first implantation step (step S10), the implantation energy is higher than the second implantation step (step S11). This can create a concentrated layer 12 of He ions located more deeply with respect to the surface of the substrate than the concentrated layer 14 of H^+ ions created during the second implantation.

The implanted starting substrate 10 is then bonded, for example by molecular bonding, to a stiffener 17, for example a silicon wafer (step S12, Figure 3C). The starting substrate 1 contains residual impurities (such as fluorine F, carbon C, etc). Furthermore, the steps of oxidation (formation of a layer of SiO_2), ion implantation and bonding may increase the amount of contamination by impurities in the starting substrate 10.

In accordance with the invention, a heat treatment step is carried out which allows the development and/or formation of microcavities in the concentrated layer 12 of He ions (i.e. 300 nm beneath the surface of the substrate 10) as well as the diffusion and trapping of the various contaminating species in said microcavities (step S13, Figure 3D). In this implementation, the microcavities of the layer 12 only constitute traps for the diffused contaminating species.

The heat treatment step may, for example, be an anneal at 400°C for 1 h to locally increase the quantity of fluorine ions and carbon impurities in the layer 12 and, as a result, to reduce the concentration of fluorine ions and carbon impurities in the remainder of the substrate and in particular in the portion corresponding to the thin film 15 to be detached. A portion of the impurities is also trapped in the concentrated layer 14 of H^+ ions, but in a smaller quantity with respect to the concentrated layer 3 of H^+ ions of the implementation described with reference to Figures 1A to 1E and 2.

This heat treatment step may be carried out equally before or after the step of binding the stiffener.

An anneal is then carried out at a temperature which is higher than the temperature of the heat treatment for trapping contaminants and which is sufficient to create, by a crystal rearrangement effect in the substrate and pressure in the microcavities of the concentrated layer 14 of H^+ ions, splitting between the thin film 15 and the portion 16 of the remainder of the substrate 10 (step S14, Figure 3E). An anneal at 500°C for 30 min [minutes] can cause the substrate 10 to fracture at the concentrated layer 14 of H^+ ions located about 230 nm beneath the surface of the substrate 10.

The thin film 15 transferred to the stiffener 17 is about 230 nm thick and contains few contaminants in its bulk and on the surface, since a portion of the contaminants has been confined to the trapping microcavities of the non-transferred layer 12 which subsists in the portion 16 of the remainder of the substrate.

A conventional polishing step (chemical-mechanical polishing) is then carried out to eliminate the perturbed zone of the surface of the thin film 15 and to reduce its roughness (step S15, Figure 3F). The thickness removed by polishing is of the order of 1500 Å. The perturbed zone may also be eliminated by selective chemical attack (etching) optionally followed by polishing to improve the surface roughness.

A final high temperature (1100°C) heat treatment step (step S16) may be carried out to improve the quality of the transferred film.

Measurements were carried out (Figures 5 to 7) to demonstrate that, for implantation conditions compatible with a subsequent step of fracture at the implanted zone, a post-implantation heat treatment can trap contaminants present in the implanted substrate.

Figures 5 to 7 show the results of measurements of the concentration of contaminants obtained in monocrystalline silicon substrates implanted under the conditions described with reference to Figures 1A and 1B and steps S1 and S2 of Figure 2 (namely implantation of H^+ species in the Si substrate at an implantation energy of about 37 keV and an implantation dose of about 5.75×10^{16} atoms/cm^2). Figures 5 to 7 show the results obtained as a function of the conditions (duration and/or temperature) of the heat treatment step in accordance with the invention (step S3, Figure 1C). The concentration measurements were carried out by secondary ion mass spectroscopy (SIMS).

Figure 5 shows the influence of the duration of the heat treatment of the invention on contaminant trapping in the case of fluorine. The four curves of Figure 5, $P_{350°C\text{-}50h}$, $P_{350°C\text{-}30h}$, $P_{350°C\text{-}18h}$, and $P_{350°C\text{-}6h}$, correspond to the concentration of fluorine observed in the thickness of the Si substrate implanted with hydrogen ions for a heat treatment carried out at a temperature of 350°C for a respective period of 50 h, 30 h, 18 h and 6 h. It should be observed that the concentration of fluorine increases significantly at a depth of about 300 nm in the substrate, which corresponds to the implanted zone in which the contaminants are trapped.

The increase in the fluorine concentration in the trapping zone (i.e. at a depth of about 300 nm in the substrate) is greater when the heat treatment at 350°C is carried out for a period of 50 h.

Figure 6 shows the influence of the temperature of the heat treatment of the invention on the trapping of contaminants in the case of fluorine. The three curves of Figure 6, $P_{350\text{-}51h}$, $P_{400\text{-}2h}$ and $P_{450°C\text{-}8mn}$, correspond to the concentration of fluorine observed in the thickness of the Si substrate implanted with hydrogen ions for a heat treatment carried out respectively at a temperature of 350°C for a period of 51 h, a temperature of 400°C for a

period of 2 h, and a temperature of 450°C for a period of 8 min. It should be observed that the concentration of fluorine increases significantly at a depth of about 300 nm in the substrate, which corresponds to the implanted zone in which the contaminants are trapped. The increase in the concentration of fluorine in the trapping zone (i.e. at a depth of about 300 nm in the substrate) is higher when the heat treatment is carried out at 350°C for a period of 51 h. However, it should be observed that a heat treatment carried out at higher temperatures (400°C and 450°C) but for periods of much less than 51 h, namely 2 h for 400°C and 8 min for 450°C, can also trap the fluorine effectively.

Figure 7 shows the influence of post-implantation heat treatment as a function of the nature of the contaminants, in this case contaminants of the organic oxygen (O) and carbon (C) type. The four curves in Figure 7, $P_{O\text{-}impl}$, $P_{O\text{-}400°C\text{-}1h}$, $P_{C\text{-}impl}$ and $P_{C\text{-}400°C\text{-}1h}$, correspond respectively to:

· the concentration of oxygen impurities observed in the thickness of the Si substrate implanted with hydrogen ions without heat treatment;

· the concentration of oxygen impurities observed in the thickness of the Si substrate implanted with hydrogen ions subjected to heat treatment carried out at a temperature of 400°C for a period of 1 h;

· the concentration of carbon impurities observed in the thickness of the Si substrate implanted with hydrogen ions without heat treatment;

· the concentration of carbon impurities observed in the thickness of the Si substrate implanted with hydrogen ions subjected to heat treatment carried out at a temperature of 400°C for a period of 1 h.

A reduction in the concentration of impurities is observed over the whole of the implanted substrate (the entire analyzed depth) and in particular over the entire thickness of the substrate (between 0 and 300 nm),

corresponding to the thin film to be transferred. In this manner, the concentration of carbon impurity is reduced by a power of ten in the future thin film to be transferred.

WHAT IS CLAIMED IS:

1. A method of fabricating a thin film, comprising:

a) at least one step of implantation by bombarding one face of a substrate formed from a semiconductor material with ions to form, at a predetermined depth in the substrate, a layer in which said implanted ions are concentrated, said concentrated layer defining a thin film in the upper portion of the substrate;

b) a step of bringing the face of the substrate into intimate contact with a stiffener;

c) a step of detaching the thin film in contact with the stiffener by splitting at the concentrated layer of ions;

wherein, after implantation step a) and before detachment step c), the method also comprises a heat treatment step to trap contaminants, which step does not cause splitting of the substrate at the concentrated layer of ions and, after step c), a step of withdrawing the zone perturbed by trapping the contaminants and by the detachment step c).

2. A method according to claim 1, wherein, in step a), the ions are ions of hydrogen gas.

3. A method according to claim 1, wherein the substrate is a substrate of silicon, germanium, silicon-germanium, gallium nitride, gallium arsenide or silicon carbide.

4. A method according to claim 1, wherein the substrate is a substrate of monocrystalline silicon, and wherein the contaminant trapping heat treatment is carried out at a temperature in the range 350°C to 450°C.

5. A method according to claim 1, wherein the contaminant trapping heat treatment is carried out at a temperature of about 350°C for a period in the range from about 18 h to 30 h.

6. A method according to claim 1, further comprising an additional implantation step consisting of bombarding the face of the substrate with ions under conditions which differ from those used for the implantation of step a), said additional implantation step being carried out at least at an implantation energy which is higher than that of step a) to create a concentrated layer of ions at a greater depth than the concentrated layer of ions created during step a).

7. A method according to claim 6, wherein, in said additional implantation step, the ions are ions of helium gas.

8. A method according to claim 7, wherein the substrate is a substrate of monocrystalline silicon, and wherein the contaminant trapping heat treatment step is carried out at a temperature of about 400°C for a period of about 1 h.

9. A method according to claim 1, wherein, in step c), a detachment stress is applied to the concentrated layer of implanted ions.

10. A method according to claim 9, wherein the detachment stress consists of applying a heat treatment and/or a mechanical detachment stress and/or a tensile stress and/or a bending stress and/or a shear stress and/or ultrasound or microwaves.

11. A method according to claim 1, wherein, in step c), an anneal is carried out at a temperature which is above the temperature of the contaminant trapping heat treatment, to cause splitting at the concentrated layer of ions formed during step a).

12. A method according to claim 1, wherein the step of withdrawing the perturbed zone is carried out by chemical-mechanical polishing or by selective chemical attack.

13. A method according to claim 1, further comprising, after step c), a step carried out at about 1000°C to anneal the thin film transferred to the stiffener.