

Description

Title: Process for reducing the boron concentration of a semiconductor layer

Technical field

5 The present disclosure relates to a process for reducing the boron concentration of a semiconductor layer, and also to a process for fabricating a semiconductor-on-insulator substrate in which said process for reducing the boron concentration can be implemented in order to rectify contamination of said semiconductor layer by boron.

10 Prior art

Photonic applications use semiconductor-on-insulator substrates. Such substrates comprise, from their back face to their front face: a carrier substrate, an electrically insulating layer, and a single-crystal semiconductor layer, referred to as the active layer.

15 Photonic devices, such as lasers, modulators, waveguides or multiplexers, may advantageously be formed at least in part in the active layer of a semiconductor-on-insulator substrate.

20 However, these applications are very sensitive to the presence of boron in the active layer. For example, for a waveguide, the presence of boron in the active layer leads to the absorption of photons which gives rise to an attenuation of an electromagnetic wave travelling in the active layer.

It is therefore sought to reduce the content of boron in the active layer.

In certain cases, the concentration of boron in the active layer may originate from the very material of said layer.

25 In particular, a semiconductor-on-insulator substrate can typically be formed by the Smart Cut™ process, comprising: forming a weakened zone in a donor substrate in order to define a semiconductor layer intended to form the active layer, bonding the donor substrate to a carrier substrate via an electrically insulating layer, and detaching the donor substrate along the weakened zone so as to transfer the semiconductor layer to the carrier substrate and the electrically insulating layer.

30 A first solution therefore consists in reducing the content of boron in the donor substrate from which the active layer originates. To this end, an N-doped donor substrate may be chosen, which has a lower boron content than the donor substrates conventionally used in the microelectronics industry, which are generally P-doped semiconductor substrates and which have a boron content of the order of 10^{15} at/cm³ or more.

35 However, even by minimizing the content of boron in the donor substrate, there is external contamination, linked in particular to the atmosphere to which the semiconductor-on-insulator substrate is subjected during its fabrication, and also to the equipment used in the fabrication processes, which is difficult to avoid.

Thus, for example, after transferring the semiconductor layer from the donor substrate to the carrier substrate, rapid heat treatment (RTA, acronym of the term "rapid thermal annealing"), intended to smooth the surface of the transferred semiconductor layer, is generally carried out. During this heat treatment, the edge of the semiconductor-on-insulator substrate is surrounded by an annular protective tool (known as an "edge guard ring") intended to uniformize the temperature within the substrate. Such a tool is typically made of polycrystalline silicon, having a high boron content in order to increase its mechanical strength. Under the effect of the temperature of the heat treatment and ambient gases, boron in the tool reacts and contaminates the edge of the substrate surrounded by the tool.

Tests have been carried out with holding tools having a lower boron content, but, despite this measure, the boron content in the active layer of the semiconductor-on-insulator substrate remains higher than the desired maximum content.

Summary

One objective of the present disclosure is to further reduce the boron concentration of the active layer of a semiconductor-on-insulator substrate, in particular for photonic applications.

For this purpose, a process is provided for reducing the boron concentration of a semiconductor layer of a semiconductor-on-insulator substrate, comprising:

- at least one heat treatment cycle, each cycle comprising a thermal oxidation of said semiconductor layer so as to form an oxide layer on the semiconductor layer, wherein, by boron segregation, boron atoms from the semiconductor layer diffuse into the oxide layer so as to create a boron concentration deficit in the semiconductor layer at the interface with the oxide layer, and

- removing the oxide layer,

thermal oxidation comprising a temperature increase under an inert atmosphere above a target thermal oxidation temperature followed by a temperature decrease down to said target thermal oxidation temperature so as to form a temperature gradient in the substrate in order to give rise to a higher rate of formation of the oxide layer at the centre of the semiconductor layer than at the edge.

Thus, owing to the segregation phenomenon, it is possible to reduce, in one or more heat treatment cycles, the boron content in the semiconductor layer. This process therefore makes it possible to compensate for boron contamination likely to occur during the fabrication of the semiconductor-on-insulator substrate. In addition, carrying out the thermal oxidation in two steps makes it possible to obtain a more uniform thickness profile of the oxide layer, the oxide growth rate obtained being higher at the centre of the substrate than at the edge thereof.

According to one embodiment of the process, said at least one heat treatment cycle comprises, after the thermal oxidation, annealing under an inert atmosphere for a time suitable

for uniformizing the concentration of boron in the semiconductor layer and/or increasing the diffusion of boron atoms towards the sacrificial oxide/semiconductor layer interface.

According to one embodiment of the process, the annealing is carried out at a temperature of between 800°C and 1200°C.

5 According to one embodiment of the process, the annealing time is between a few seconds and several hours, for example between two seconds and twenty hours.

According to one embodiment of the process, the thermal oxidation is carried out at a temperature of between 800°C and 1200°C under an oxidizing atmosphere.

10 According to one embodiment of the process, the thermal oxidation is carried out under controlled conditions in order to form the oxide layer with a greater thickness at the centre of the semiconductor layer than at the edge of said semiconductor layer.

According to one embodiment of the process, the semiconductor layer has a thickness of between 0.01 and 1 µm.

15 According to one embodiment of the process, in each treatment cycle, the thermal oxidation and the annealing are carried out in the same furnace.

According to one embodiment, the process, comprises at least a first and a second treatment cycle.

According to one embodiment, the process comprises, between the first and second treatment cycles, removal of the oxide layer formed during the first heat treatment cycle.

20 According to one embodiment, the second treatment cycle directly follows the first treatment cycle, the oxide layer formed during the first and second treatment cycles being removed after the second treatment.

According to one embodiment, the semiconductor layer has an initial boron concentration of greater than or equal to 10^{15} at/cm³.

25 According to one embodiment, the semiconductor layer has, after removal of the oxide layer, a final boron content of less than or equal to 5×10^{14} at/cm³.

According to one embodiment, the removal of the oxide layer is carried out by selective chemical etching.

30 The present disclosure further relates to a process for fabricating a semiconductor-on-insulator substrate, comprising:

- forming a weakened zone by implanting ion species in a donor substrate in order to define a semiconductor layer;
- joining the donor substrate to a carrier substrate via an electrically insulating layer,
- 35 - detaching the donor substrate along the weakened zone in order to transfer the semiconductor layer to the carrier substrate, so as to form the semiconductor-on-insulator substrate,

- carrying out the proposed process for reducing the boron concentration of the semiconductor layer.

According to one embodiment, the fabrication process comprises, after transferring the semiconductor layer onto the carrier substrate, at least one rapid heat treatment for smoothing the surface of said semiconductor layer, each rapid heat treatment being performed before the process for reducing the boron concentration of the semiconductor layer is carried out.

The present disclosure further relates to a process for fabricating a photonic device, comprising the fabrication of a semiconductor-on-insulator substrate according to the fabrication process according to the present disclosure, and the formation of a passive photonic component in the semiconductor layer having a reduced concentration of boron.

Brief description of the drawings

Other features and advantages will become apparent from the following detailed description, with reference to the appended drawings, in which:

- Figure 1 is a schematic cross-sectional view of the formation of a weakened zone by implantation of ion species in a donor substrate;

- Figure 2 is a schematic cross-sectional view of the formation of an electrically insulating layer on a carrier substrate;

- Figure 3 is a schematic cross-sectional view of the bonding of the donor substrate of Figure 1 to the carrier substrate of Figure 2;

- Figure 4 is a schematic cross-sectional view of the semiconductor-on-insulator substrate obtained after detachment of the donor substrate along the weakened zone;

- Figure 5 is a schematic cross-sectional view of the thermal oxidation of the active layer of the semiconductor-on-insulator substrate of Figure 4;

- Figure 6 is a schematic cross-sectional view of the semiconductor substrate of figure 5 after removal of the oxide layer;

- Figure 7a is a schematic illustration of a step of implanting species in a semiconductor substrate;

- Figure 7b is a schematic illustration of an embodiment comprising a thermal oxidation step;

- Figure 8 is a graph showing curves of boron concentration as a function of depth in the semiconductor-on-insulator substrate, respectively on conclusion of: a standard fabrication process comprising a smoothing rapid heat treatment (I), a fabrication process based on a boron-depleted donor substrate and the use of an annular tool for protecting the substrate during a smoothing rapid heat treatment designed to minimize contamination by boron (II) and a process carried out under the same conditions as the process (II) followed by the proposed process for reducing the boron concentration (III).

For the sake of legibility of the figures, the various layers have not necessarily been shown to scale.

Detailed description of embodiments

Figures 1 to 4 represent, in a manner known from the prior art, a Smart Cut TM process for fabricating a semiconductor-on-insulator substrate, successively comprising at least the following steps:

- implanting ion species in a first semiconductor substrate 10, referred to as the donor substrate, so as to form a weakened zone 11, as shown in Figure 1, said weakened zone limiting a layer 12 to be transferred;

- forming, on a second semiconductor substrate 20, referred to as the receiver substrate, an electrically insulating layer 21, in particular obtained by oxidation of a surface portion of the substrate 20, as shown in Figure 2;

- transferring a layer 12 of the donor substrate 10 by bonding to the receiver substrate 20, via the electrically insulating layer 21, then by detaching the donor substrate 10 along the weakened zone 11, as shown in Figures 3 and 4. A semiconductor-on-insulator substrate 1 is thus obtained (cf. Figure 4).

Advantageously, the substrate 1 is configured for photonic applications. Consequently, the thickness of the transferred layer 12 is preferentially between 100 and 600 nm and the thickness of the electrically insulating layer is preferentially between 200 nm and 3000 nm.

According to one alternative, the electrically insulating layer 21 can be formed on the donor substrate 10 before the implantation step.

The present disclosure relates to a process that aims to reduce the boron concentration of semiconductor layer 12 of the substrate.

In its general embodiment, this process involves, after the transfer step, a heat treatment cycle. This cycle comprises a step of thermal oxidation of the semiconductor layer 12, in order to form a sacrificial oxide layer 120 on the semiconductor layer, this step being shown in Figure 5. During oxidation, a segregation phenomenon occurs, during which boron atoms move from the semiconductor layer to the sacrificial oxide layer 120, thus reducing the boron concentration of the semiconductor layer 12. The heat treatment cycle also comprises a heat treatment step, carried out either after the oxidation step or simultaneously therewith. This heat treatment step allows a redistribution of the boron atoms in the semiconductor layer 12. Finally, and with reference to Figure 6, the sacrificial oxide layer 120 is removed so as to expose the semiconductor layer 12.

The thermal oxidation may be carried out at a temperature between 800°C and 1200°C, under an oxidizing atmosphere.

Advantageously, the process is carried out under conditions which already enable, in a known manner, a significant reduction in the boron content of the semiconductor substrate. In

particular, an N-doped substrate with a reduced content of boron may be used as donor substrate. It is also possible to use an annular protective tool with a low boron content.

According to one embodiment, the process may comprise several heat treatment cycles, in particular two heat treatment cycles. This enables better diffusion of boron at the interface between the semiconductor layer 12 and the sacrificial oxide layer 120. It is then possible to carry out the heat treatment cycles directly one after the other, by removing the oxide layer 120 after the last heat treatment cycle, or by removing the oxide layer 120 formed after each heat treatment cycle. Removing the oxide layer 120 after the last heat treatment cycle has the advantage of not requiring the removal of the substrate from the furnace between the various heat treatment cycles, thus facilitating the industrialization of the process.

In order to further improve the diffusion of boron at the interface between the semiconductor layer 12 and the sacrificial oxide layer 120, the heat treatment step may be an annealing under an inert atmosphere. Such an annealing may advantageously take place at a temperature suitable for uniformizing the boron concentration in the semiconductor layer 12 and/or increasing the diffusion of boron atoms towards the sacrificial oxide 120/semiconductor layer 12 interface. Such an annealing may advantageously be carried out at a temperature of between 800°C and 1200°C, and last between a few seconds and several hours or even several tens of hours.

So as to minimize the time and material resources required to carry out the proposed process, the heat treatment cycles and the heat treatment step can be performed in the same furnace. Thus, only a single furnace is required for the implementation of the process, and no removal of the substrate from the furnace is necessary before the step of removing the oxide layer 120.

Following the implantation step of the Smart Cut™ process, the inventors noted that the uniformity of the implantation depth of the species is degraded. This non-uniformity of implantation depth is revealed by a non-uniformity of thickness of the active layer, which adopts a typically concave or convex profile, this being detrimental to the quality of the components subsequently formed in this active layer. Such a concave profile is illustrated in Figure 7a. According to an embodiment illustrated in Figure 7b, the thermal oxidation is carried out under controlled conditions, so as to form the oxide layer with a thickness greater at the centre of the semiconductor layer 12 than at its edges. Thus, this oxidation step consumes more material from the semiconductor layer 12 at the centre than at the edge of the substrate, thus compensating, at least in part, for the non-uniformity of thickness due to the implantation step of the process for fabricating the semiconductor-on-insulator substrate.

In order to obtain such an oxide layer 120 with a thickness greater at the centre than at its edges, thermal oxidation can be carried out in two steps. The temperature is initially increased under an inert atmosphere beyond a target thermal oxidation temperature, then the temperature is decreased to this target temperature. An oxidizing atmosphere is introduced

during this second, decrease step. This makes it possible to cool the substrate at its edges faster than at its centre, so as to obtain a higher oxide growth rate at the centre of the substrate than at its edges. Thus, an oxide layer is formed with a thickness profile more suitable for improving the uniformity of the semiconductor layer 12 after deoxidation, than if an oxide layer
 5 had been formed with a simple increase to the target oxidation temperature. In the latter case, the thickness profile of the oxide layer formed will be similar to the initial thickness profile of the transferred semiconductor layer 12.

The semiconductor layer may, before carrying out the proposed process, have an initial boron concentration of greater than or equal to 10^{15} at/cm³. Specifically, the P-doped
 10 substrates generally used in the fabrication of semiconductor-on-insulator substrates have a boron content of this order. Following the use of the process, the semiconductor layer is advantageously reduced to a boron content of less than or equal to 5×10^{14} at/cm³.

According to one embodiment, the removal of the oxide layer 120 is carried out by selective chemical etching, which is particularly suitable for producing semiconductor-on-
 15 insulator substrates. It may in particular be hydrofluoric acid etching. Alternatively, it may be dry reactive-ion etching, which at the same time has a good degree of anisotropy, making it possible to etch the substrate mainly in its thickness direction, and not to significantly damage the substrate.

The present disclosure further relates to a process for fabricating a semiconductor-on-
 20 insulator substrate, comprising:

- forming a weakened zone 11 by implanting ion species in a donor substrate 10 in order to define a semiconductor layer 12;
- joining the donor substrate 10 to a carrier substrate 20 via an electrically insulating layer 21,
- 25 - detaching the donor substrate along the weakened zone 11 in order to transfer the semiconductor layer 12 to the carrier substrate 20, so as to form the semiconductor-on-insulator substrate 1,
- carrying out the process for reducing the boron concentration described above.

One or more rapid heat treatment (RTA) steps may be provided before carrying out the
 30 process for reducing the boron concentration, so as to smooth the surface of the semiconductor layer 12.

Figure 8 shows curves of boron concentration as a function of the depth in the semiconductor-on-insulator substrate, respectively on conclusion of: a standard fabrication process comprising a smoothing rapid heat treatment (I); a fabrication process based on a
 35 boron-depleted donor substrate and the use of an annular tool for protecting the substrate during a smoothing rapid heat treatment designed to minimize contamination by boron (II); and a process carried out under the same conditions as the process (II) followed by the proposed process for reducing the boron concentration (III). It can be seen that the proposed fabrication

process considerably reduces the boron content of the upper layer of the semiconductor substrate obtained, the upper semiconductor layer corresponding to depths of less than 0.5 micrometres. In particular, the reduction in boron content obtained is particularly sizeable beyond a thickness of approximately 0.1 micrometres (the peak located at a depth between 0 and 0.04 μm is a measurement artifact). On the other hand, a peak in boron content is observed at a depth of about 0.5 μm , which corresponds to the depth of the electrically insulating layer.

Lastly, the present disclosure also relates to a process for fabricating a photonic device, comprising the fabrication of a semiconductor-on-insulator substrate according to the process described above and the formation of a passive photonic component in the semiconductor layer 12. The passive photonic component thus obtained will therefore have a reduced concentration of boron. It may be for example, but non-limitingly, a waveguide, a modulator or a multiplexer.

Claims

1. Process for reducing the boron concentration of a semiconductor layer (12) of a semiconductor-on-insulator substrate (1), comprising:

- at least one heat treatment cycle, each cycle comprising a thermal oxidation of said semiconductor layer (12) so as to form an oxide layer (120) on the semiconductor layer (12), wherein, by boron segregation, boron atoms from the semiconductor layer (12) diffuse into the oxide layer (120) so as to create a boron concentration deficit in the semiconductor layer (12) at the interface with the oxide layer (120), and

- removing the oxide layer (120),

in which the thermal oxidation comprises a temperature increase under an inert atmosphere above a target thermal oxidation temperature followed by a temperature decrease down to said target thermal oxidation temperature so as to form a temperature gradient in the substrate in order to give rise to a higher rate of formation of the oxide layer (120) at the centre of the semiconductor layer than at the edge.

2. Process according to the preceding claim, wherein said at least one heat treatment cycle comprises, after the thermal oxidation, annealing under an inert atmosphere for a time suitable for uniformizing the concentration of boron in the semiconductor layer (12) and/or increasing the diffusion of boron atoms towards the sacrificial oxide (120)/semiconductor layer (12) interface.

3. Process according to Claim 2, wherein the annealing is carried out at a temperature of between 800°C and 1200°C.

4. Process according to one of Claims 1 to 3, wherein the thermal oxidation is carried out at a temperature of between 800°C and 1200°C under an oxidizing atmosphere.

5. Process according to one of Claims 1 to 4, wherein the semiconductor layer (12) has a thickness of between 0.01 and 1 µm.

6. Process according to one of Claims 2 to 5, wherein, in each treatment cycle, the thermal oxidation and the annealing are carried out in the same furnace.

7. Process according to any one of Claims 1 to 6, comprising at least a first and a second treatment cycle.

8. Process according to Claim 7, comprising, between the first and second treatment cycles, removal of the oxide layer (120) formed during the first heat treatment cycle.

9. Process according to Claim 7, wherein the second treatment cycle directly follows the first treatment cycle, the oxide layer (120) formed during the first and second treatment cycles being removed after the second treatment.

10. Process according to one of Claims 1 to 9, wherein the semiconductor layer (12) has an initial boron concentration of greater than or equal to 10^{15} at/cm³.

11. Process according to Claim 10, wherein the semiconductor layer (12) has, after removal of the oxide layer (120), a final boron content of less than or equal to 5×10^{14} at/cm³.

12. Process according to one of Claims 1 to 11, wherein the removal of the oxide layer (120) is carried out by selective chemical etching.

13. Process for fabricating a semiconductor-on-insulator substrate (1), comprising:

- forming a weakened zone (11) by implanting ion species in a donor substrate (10) in order to define a semiconductor layer (12);
- joining the donor substrate (10) to a carrier substrate (20) via an electrically insulating layer (21),
- detaching the donor substrate (10) along the weakened zone (11) in order to transfer the semiconductor layer (12) to the carrier substrate (20), so as to form the semiconductor-on-insulator substrate (1),
- carrying out the process for reducing the boron concentration of the semiconductor layer (12) according to one of Claims 1 to 12.

14. Process according to Claim 13, comprising, after transferring the semiconductor layer (12) onto the carrier substrate (20), at least one rapid heat treatment for smoothing the surface of said semiconductor layer (12), each rapid heat treatment being performed before the process for reducing the boron concentration of the semiconductor layer (12) is carried out.

15. Process for fabricating a photonic device, comprising the fabrication of a semiconductor-on-insulator substrate according to the process of Claim 13 or Claim 14, and the formation of a passive photonic component in the semiconductor layer (12) having a reduced concentration of boron.