

## **METHOD FOR SEPARATING A REMOVABLE COMPOSITE STRUCTURE BY MEANS OF A LIGHT FLUX**

### **FIELD OF THE INVENTION**

5       The present invention relates to a composite structure that can be dismantled by applying a light flux, and to a method for separating such a structure.

### **BACKGROUND OF THE INVENTION**

10       It is known practice, in the field of microelectronics, optics and optoelectronics, to produce a dismantlable composite structure comprising a useful layer and a substrate, said structure being intended to be subsequently treated in order to separate the useful layer from the substrate.

15       This is the case, for example, when the substrate is a growth substrate for the formation by epitaxy of the useful layer, and when it is then desired to separate the useful layer from the substrate in order to use it alone or to transfer it to a final carrier.

      To this end, there is arranged within the structure, between the useful layer and the substrate, a sacrificial layer which is intended to be at least partly broken down during the separation treatment.

20       One particular separation technique is known under the term "laser lift-off" (LLO), in which a light flux is used to break down the sacrificial layer. This technique takes advantage of the differences in optical absorption and temperature resistance properties of the materials forming the structure. Thus, the substrate is substantially transparent to said light flux, while the sacrificial layer strongly absorbs said flux. Consequently, when the composite structure is irradiated by applying the light flux through the substrate, the sacrificial layer heats up substantially and then dissociates when the temperature exceeds a given temperature, called the dissociation temperature. What is thus obtained is the useful layer on the one hand and, on the other hand, the substrate which may be reused, for example to form a new composite structure.

30       One drawback of this method is that due to the proximity between the layer to be separated and the sacrificial layer, the layer to be separated may also be raised to a high temperature by thermal conduction from the sacrificial layer. Such heating of the layer to be separated may result in a degradation of some of its properties, in particular in the case where the substrate and the layer to be separated have substantially different coefficients of thermal expansion.

35       Document WO 2015/019018 describes a dismantlable composite structure in which a thermal barrier layer is interposed between the sacrificial layer and the layer to be separated. Said thermal barrier layer is substantially transparent to the light flux so

as not to heat up and is thick enough to maintain the layer to be separated at a temperature below a determined threshold for the duration of the exposure to the light flux.

However, for certain materials of the layer to be separated and/or of the final carrier where applicable, such a thermal barrier layer may not be sufficient.

Thus, for example, in the case where the layer to be separated comprises a stack of ferromagnetic materials such as CoFeB/MgO, an interdiffusion of the atoms takes place from a temperature of about 400 to 600°C. In the case where the layer to be separated is made of graphene, a degradation of the electrical properties takes place from a temperature of 600°C. In the case of a layer to be separated made of molybdenite (MoS<sub>2</sub>), a modification of the hybridization and a reaction with other materials may take place from a temperature of about 450 to 600°C. In the case where the layer to be separated is made of a phase-change alloy, such as GeSbTe, melting and a transition to the amorphous phase take place from about 600°C.

Likewise, depending on the composition of the final carrier to which the layer to be separated is to be transferred, said carrier may be affected by the thermal budget applied in order to dissociate the sacrificial layer. Thus, for example, if the final carrier comprises electronic circuits containing copper, extrusion of the copper lines may take place from 400°C. In the case where the final carrier is made of a polymer material (for example a plastic material), it may decompose from 200°C.

In such cases, in order to carry out the separation at low temperature, one possible technique is to remove the substrate via an etch from the rear face of the layer to be separated, in such a way that said substrate cannot be recycled for another use.

Another conceivable method based on the LLO technique, when the final carrier is sensitive to temperature, is to transfer the layer to be separated to a temporary substrate which is not liable to be affected by the thermal budget for dissociation of the sacrificial layer, then to transfer the layer to be separated to the final carrier. However, this method takes longer and is more expensive than the LLO method since it requires that the layer of interest be transferred twice.

## **BRIEF DESCRIPTION OF THE INVENTION**

Embodiments of the invention seek to overcome the aforementioned drawbacks and in particular to design a dismantlable composite structure comprising a sacrificial layer capable of dissociating through the application of a limited thermal budget (typically corresponding to a temperature of lower than 500°C) generated through the absorption of a light flux.

According to an aspect of the present invention, there is provided a method for separating a composite structure that is dismantlable by means of a light flux, the method including: providing the dismantlable composite structure comprising successively: a substrate, an optically absorbent layer made of a material suitable for at least partially absorbing a light flux, the substrate being substantially transparent to the light flux, a sacrificial layer suitable for dissociating under the application of a temperature higher than a dissociation temperature,

made of a material different from that of the optically absorbent layer, at least one layer to be separated, applying a light flux through the substrate, the light flux being absorbed at least in part by the optically absorbent layer, so as to heat the optically absorbent layer, heating the sacrificial layer by thermal conduction from the optically absorbent layer, up to a temperature higher than or equal to the dissociation temperature, dissociating the sacrificial layer under the effect of the heating.

To this end, an embodiment of the invention proposes a composite structure that can be dismantled by means of a light flux, comprising successively:

- a substrate,
- an optically absorbent layer made of a material suitable for at least partially absorbing a light flux, the substrate being substantially transparent to said light flux,
- a sacrificial layer suitable for dissociating under the application of a temperature higher than a dissociation temperature, made of a material different from that of the optically absorbent layer,
- at least one layer to be separated.

The term "composite" is understood to mean that the structure is formed of a stack of different materials, exhibiting in particular different properties in terms of optical absorption and temperature resistance.

The term "dismantlable" is understood to mean that the composite structure is able to separate along a plane parallel to its main surfaces, into two parts which each retain their integrity, with the exception of a sacrificial layer which is located at the interface between the two parts and which dissociates to allow said separation.

The term "substantially transparent material" is understood to mean a material that allows at least 90% of the light flux that it receives to pass. In other words, the product of the thickness of said material and of the coefficient of absorption of the light flux by said material is less than 0.1.

The term "optically absorbent material" is understood to mean a material that absorbs at least 90% of the light beam that it receives. In other words, the product of the thickness of said material and of the coefficient of absorption of the light flux by said material is greater than 2.3. The optical absorption coefficient, at the wavelength of the light flux, is preferably greater than  $10^5 \text{ cm}^{-1}$ .

The terms "on" and "between" referring to the relative position of two layers do not necessarily imply direct contact between said layers, unless such contact is specified.

By providing a sacrificial layer that is distinct from the optically absorbent layer, in comparison with the known method in which the sacrificial layer is merged with the optically absorbent layer, the composite structure according to embodiments of the invention has several advantages. Specifically, the thickness of the sacrificial layer may be minimized. Because of this, the amount of heat present after dissociation of said layer on the side of the layer to be separated will be lower. In addition, the sacrificial layer itself contributes to distancing the optically absorbent layer from the layer to be separated. As a result, the

composite structure may be separated using a lower thermal budget, which allows the use of a layer to be separated and/or of a final carrier which are sensitive to temperature as mentioned above.

According to other advantageous but optional features of said structure, considered alone or in combination when this is appropriate:

- the sacrificial layer is in contact with the optically absorbent layer;
- the sacrificial layer is made of a material that is substantially transparent to said light flux;
- the structure further comprises a first thermal barrier layer that is substantially transparent to said light flux, between the substrate and the optically absorbent layer;
- the structure further comprises a second thermal barrier layer between the sacrificial layer and the layer to be separated;
- the first and/or the second thermal barrier layer has a linear thermal conductivity coefficient of less than  $10 \text{ W m}^{-1} \text{ K}^{-1}$ ;
- the first and/or the second thermal barrier layer comprises at least one of the following materials: silica ( $\text{SiO}_2$ ), alumina ( $\text{Al}_2\text{O}_3$ );
- the structure further comprises a first film suitable for reflecting or absorbing the light flux, between the sacrificial layer and the layer to be separated;
- said first film comprises at least one of the following materials: silicon, silica ( $\text{SiO}_2$ ), silicon carbide ( $\text{SiC}$ ), molybdenum, silicon nitride ( $\text{Si}_3\text{N}_4$ );
- the structure further comprises, between the sacrificial layer and the layer to be separated, a second film suitable for distributing the heat over the entire area of the structure;
- said second film comprises at least one of the following materials: alumina ( $\text{Al}_2\text{O}_3$ ), silica ( $\text{SiO}_2$ ), polycrystalline aluminum nitride ( $\text{AlN}$ ), polycrystalline silicon;
- the substrate comprises at least one of the following materials: sapphire, quartz;
- the optically absorbent layer comprises at least one of the following materials: silicon nitride ( $\text{Si}_3\text{N}_4$ ), polycrystalline silicon, polycrystalline silicon carbide ( $\text{SiC}$ );
- the sacrificial layer comprises at least one of the following materials: silicon nitride ( $\text{Si}_3\text{N}_4$ ), polycrystalline aluminum nitride ( $\text{AlN}$ ), polycrystalline gallium nitride ( $\text{GaN}$ ), indium tin oxide (ITO);
- the layer to be separated comprises at least one of the following materials: a metal, such as copper; a group IV material having a hexagonal crystal structure, such as graphene; a piezoelectric, ferromagnetic or ferroelectric material; a phase-change alloy, such as  $\text{GeSbTe}$ .

Another embodiment of the invention relates to a method for separating a dismantlable composite structure such as described above.

Said method comprises:

- applying a light flux through the substrate, said light flux being absorbed at least in part by the optically absorbent layer, so as to heat said optically absorbent layer,
- heating the sacrificial layer by thermal conduction from the optically absorbent layer, up to a temperature higher than or equal to the dissociation temperature,

- dissociating the sacrificial layer under the effect of said heating.

According to other advantageous but optional features of said method, considered alone or in combination when this is appropriate:

- the product of the thickness of the substrate and of the coefficient of absorption of the light flux by the substrate is less than 0.1;
- the product of the thickness of the optically absorbent layer and of the coefficient of absorption of the light flux by said layer is greater than 2.3;
- the light flux is applied in a pulsed manner;
- the wavelength of the light flux is between 100 and 12 000 nm;
- before the application of said light flux, the method comprises a step of bonding the composite structure to a carrier, the dissociation of the sacrificial layer leading to the transfer of the layer to be separated to the carrier;
- the carrier comprises at least one of the following materials: a semiconductor material, such as silicon; a metal, such as copper; a polymer.

Another embodiment of the invention relates to a method for producing a dismantlable composite structure such as described above. The method includes the following steps:

- providing the substrate,
  - forming, on the substrate, an optically absorbent layer made of a material suitable for at least partially absorbing a light flux, the substrate being substantially transparent to said light flux,
  - forming the layer to be separated on the optically absorbent layer,
- the method being characterized in that it comprises the formation of the sacrificial layer between the optically absorbent layer and the layer to be separated, said sacrificial layer being made of a material different from that of the optically absorbent layer.

Advantageously, the formation of the layer to be separated is implemented at a temperature lower than the dissociation temperature of the sacrificial layer.

The formation of the layer to be separated may comprise the deposition or the bonding of said layer on or to a seed layer. Said seed layer may comprise at least one of the following materials: platinum, nickel, copper.

## **BRIEF DESCRIPTION OF THE DRAWINGS**

Other features and advantages of the invention will emerge from the detailed description which follows, with reference to the appended drawings, in which:

- figures 1A and 1B schematically illustrate a dismantlable composite structure according to two embodiments of the invention,
- figure 2 schematically illustrates the bonding of the structure of figure 1A to a carrier,
- 5       - figure 3 schematically illustrates the application of a light flux to the dismantlable composite structure bonded to said carrier,
- figure 4 schematically illustrates the separation of the composite structure following the dissociation of the sacrificial layer,
- figure 5 schematically illustrates the structure obtained on completion of said
- 10       separation, comprising the layer to be separated transferred to the carrier,
- figures 6A to 6C show thermal simulation results showing, respectively, the heating within the dismantlable composite structure during a pulse of the light flux and the homogenization of the temperature within said composite structure after the dissociation of the sacrificial layer, for different durations after the laser pulse and the
- 15       dissociation of the sacrificial layer, and the change in temperature at the seed layer over time, during and after a pulse of the light flux, for a first type of composite structure,
- figures 7A and 7B respectively illustrate the maximum temperature at the seed layer and the heat required for the separation per unit area as a function of the pulse duration of the light flux, for a known structure (in which the optically absorbent
- 20       layer and the sacrificial layer are merged and therefore form a single layer of  $\text{Si}_3\text{N}_4$ ), and for a structure according to the invention (in which the optically absorbent layer is made of SiC and the sacrificial layer is made of  $\text{Si}_3\text{N}_4$ ),
- figure 7C shows the maximum temperature at the seed layer as a function of the pulse duration of the light flux, for different compositions of the first type of composite
- 25       structure,
- figures 8A and 8B respectively show the maximum temperature at the interface between the layer to be transferred and the carrier, and the power to be transmitted through the substrate in order to dissociate the sacrificial layer, as a function of the pulse duration, for different compositions of a second type of composite structure,
- 30       - figures 9A to 9C show thermal simulation results showing, respectively, the heating within the dismantlable composite structure during a pulse of the light flux and the homogenization of the temperature within said composite structure after the dissociation of the sacrificial layer, for different pulse durations, and the change in temperature at the interface between the seed layer and the layer to be separated over
- 35       time, during and after a pulse of the light flux.

For the sake of legibility of the figures, the illustrated elements are not necessarily shown to scale. Moreover, elements denoted by the same reference signs in the various figures are identical.

## 5           **DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION**

The context of the invention is that of the separation of a composite structure through the dissociation of a layer of said structure under the effect of heating caused by the application of a light flux through at least part of the structure.

10           In comparison with the structure described in the aforementioned document WO 2015/019018, the invention proposes decoupling the portion of the structure which is heated by optical absorption from the portion of the structure which dissociates under the effect of said heating by forming, in said structure, an optically absorbent layer that is distinct from the sacrificial layer. In particular, unlike the optically absorbent layer, the sacrificial layer is made of a material that is substantially transparent to the light flux and  
15           capable of dissociating under the application of a temperature higher than a dissociation temperature, said temperature being reached by heating the optically absorbent layer through the absorption of the light flux.

            In general, as illustrated in figure 1A, the composite structure 100 successively comprises at least one substrate 1 that is substantially transparent to the light flux, the  
20           optically absorbent layer 2, the sacrificial layer 3 and a layer 4 (or a stack of layers) to be separated from the rest of the structure.

            The irradiation by the light flux is performed through the face of the substrate opposite the layer to be separated. Specifically, the layer to be separated is not necessarily transparent to the light flux; however, heating caused by at least partial  
25           absorption of said light flux could damage said layer to be separated. The sacrificial layer is interposed between the optically absorbent layer and the layer to be separated. Thus, it contributes to forming a thermal barrier between the optically absorbent layer which heats up substantially by absorbing the light flux, and the layer to be separated.

            Preferably, the sacrificial layer is in contact with the absorbent layer, so as to  
30           maximize the heat transfer from the absorbent layer to the sacrificial layer.

            The substrate 1 is chosen from a material that is substantially transparent to the light flux to be applied in order to dissociate the sacrificial layer.

            Advantageously, the substrate may be a bulk substrate or consist of a stack of layers of different materials, as long as each of said materials is substantially transparent  
35           to the light flux.

            According to a preferred embodiment, the substrate comprises at least one of the following materials: sapphire, quartz.

The material of the optically absorbent layer 2 is chosen so as to be highly absorbent at the wavelength of the light flux.

Advantageously, the layer 2 comprises at least one of the following materials: silicon nitride ( $\text{Si}_3\text{N}_4$ ), polycrystalline silicon, polycrystalline silicon carbide ( $\text{SiC}$ ),  
5 molybdenum ( $\text{Mo}$ ).

The sacrificial layer 3 is a layer that is distinct from the layer 2, advantageously made of a material that is substantially transparent to the light flux. The material of the sacrificial layer is chosen so as to start dissociating from what is called a dissociation temperature. Starting from this dissociation temperature, decohesion of the chemical  
10 bonds of the material of the sacrificial layer is observed, leading to separation of the composite structure at said sacrificial layer. The material of the optically absorbent layer, on the other hand, is stable to a temperature above the dissociation temperature.

Advantageously, the sacrificial layer comprises at least one of the following materials: silicon nitride ( $\text{Si}_3\text{N}_4$ ), polycrystalline aluminum nitride ( $\text{AlN}$ ), polycrystalline  
15 gallium nitride ( $\text{GaN}$ ), indium tin oxide ( $\text{ITO}$ ). The dissociation temperature of these different materials is generally between 1000 and 2500°C.

The sacrificial layer is not substantially heated by absorbing the light flux, but through thermal conduction from the optically absorbent layer. Since the sacrificial layer begins to dissociate as soon as the temperature to which it is exposed reaches the  
20 dissociation temperature of said layer, the thermal budget applied to the layer to be separated is lower than the thermal budget which would be applied to said layer if it were in contact with the optically absorbent layer.

Furthermore, using two distinct layers for optical absorption and dissociation means that a relatively thin sacrificial layer (thinner than the sacrificial layer of the prior art) can be used. Specifically, while in the case where the sacrificial layer is merged with  
25 the optical absorption layer, said layer must be thick enough (typically, of the order of a few hundred nanometers) to store the heat required for its own dissociation, the only function of the sacrificial layer is to start to break down from a certain temperature and it may therefore be very thin (of the order of a few tens of nanometers).

30 Since the invention makes it possible to decrease the thermal budget of the layer to be separated, said layer may be formed from a wide variety of materials.

For example, the layer to be separated advantageously comprises at least one of the following materials: a metal, such as copper; a group IV material having a hexagonal crystal structure, such as graphene; a piezoelectric, ferromagnetic or ferroelectric  
35 material; a phase-change alloy, such as  $\text{GeSbTe}$  for example.

Said composite structure may be obtained by successively growing the constituent layers on the substrate 1. Certain steps in the production of the composite structure may also include layer transfer or bonding steps.

In any event, the dissociation temperature of the sacrificial layer must be higher than the temperature at which the layer to be separated is deposited or bonded, in order to avoid any untimely dissociation of the sacrificial layer during the production of the composite structure.

The composite structure may advantageously comprise one or more additional layers, used alone or in combination, which produce the additional effects described below with reference to figure 1B.

Figure 1B illustrates an embodiment that combines all of these additional functional layers, but, as indicated above, the composite structure could comprise only some of these layers, as long as it comprises at least the layers described with reference to figure 1A.

Between the substrate 1 and the optically absorbent layer 2 is arranged a first layer 5 forming a thermal barrier. The layer 5 is made of a material that is substantially transparent to the light flux and exhibits low thermal conductivity. The term "low thermal conductivity" is understood in the present text to mean a linear thermal conductivity coefficient of less than  $10 \text{ W.m}^{-1}.\text{K}^{-1}$ .

A second thermal barrier layer 5 is arranged on the sacrificial layer 3. Since the layer 5 is made of a material with low thermal conductivity, it makes it possible to improve the thermal insulation of the layer 4 to be separated.

Advantageously, each of the layers 5 comprises at least one of the following materials: silica ( $\text{SiO}_2$ ), alumina ( $\text{Al}_2\text{O}_3$ ).

The layers 5 make it possible to confine the heat to the portion of the composite structure which they delimit, namely the optically absorbent layer and the sacrificial layer. Thus, the dissociation temperature of the sacrificial layer is reached more quickly than in the absence of the thermal barrier layers.

A film 6 (or a stack of films) suitable for reflecting the light flux, or for absorbing the part of said flux transmitted through the optically absorbent layer, is arranged on the second thermal barrier layer 5.

Said film 6 advantageously comprises at least one of the following materials: silicon, silica ( $\text{SiO}_2$ ), silicon carbide ( $\text{SiC}$ ), molybdenum, silicon nitride ( $\text{Si}_3\text{N}_4$ ). The film 6 may advantageously comprise a Bragg mirror-type stack. Said stack may optionally perform the function of a thermal barrier and thus replace the second layer 5.

Said film 6 makes it possible to prevent part of the light flux from being transmitted to the layer to be separated, which has the effect of decreasing the thermal budget applied to said layer and of avoiding energy losses.

Furthermore, a film 7 (or a stack of films) exhibiting a certain thermal inertia and suitable for distributing the heat over the entire area of the structure is arranged on the film 6.

Said film 7 is characterized by a product thickness x density x specific heat capacity.

Said film 7 comprises at least one of the following materials: alumina ( $\text{Al}_2\text{O}_3$ ), silica ( $\text{SiO}_2$ ), polycrystalline aluminum nitride (AlN), polycrystalline silicon.

Finally, a seed layer 8 is arranged on the film 7, in direct contact with the layer 4 to be transferred. The seed layer is chosen so as to facilitate the bonding or the deposition of the layer 4 to be separated, depending on the way in which said layer is formed.

The seed layer 8 may comprise at least one of the following materials: platinum, nickel, copper.

In the case where the layer to be separated is to be transferred to a carrier with a view to later use, the composite structure is joined to said carrier by means of the layer to be separated. The decrease in the separation thermal budget described above is also beneficial to the carrier, in particular if the latter is sensitive to temperature. The invention therefore also makes it possible to use a greater variety of carriers, in particular made of polymer material or of metal.

In general, the carrier may comprise at least one of the following materials: a semiconductor material, such as silicon; a metal, such as copper; a polymer.

Figure 2 illustrates the bonding of the composite structure of figure 1A to a carrier 200. The bonding may be preceded by any suitable surface preparation step with a view to strengthening the bonding energy. Alternatively, the carrier may be deposited on the layer to be separated, provided that the thermal budget implemented for this deposition is sufficiently low so as not to cause dissociation of the sacrificial layer.

Figure 3 schematically illustrates the irradiation of the composite structure bonded to the carrier by a laser beam (represented by the arrow). Said beam passes through the substrate 1 (and, where applicable, the first thermal barrier layer) and is absorbed by the optically absorbent layer, which heats up.

Advantageously, the light flux is applied in a pulsed manner. The duration of each pulse is of the order of a few tens of nanoseconds. This duration is chosen according to the power of the laser and the temperature to be reached in the optically absorbent layer in order to be able to dissociate the sacrificial layer.

The wavelength of the laser is chosen in relation to the materials of the layers constituting the composite structure. In particular, the substrate and the one or more thermal barrier layers, and the sacrificial layer, are substantially transparent at the wavelength of the laser, unlike the optically absorbent layer.

5 In general, the wavelength of the laser may be between 100 and 12 000 nm. For a quartz substrate, the wavelength of the laser is advantageously of the order of 150 to 700 nm. For a silicon substrate, the wavelength of the laser is advantageously of the order of 1000 to 12 000 nm.

10 With reference to figure 4, the sacrificial layer 3 dissociates under the effect of the heat generated in the electrically absorbent layer 2. The composite structure therefore separates into two parts: a first part which comprises the substrate 1 and the optically absorbent layer 2, on the one hand, and a second part which comprises the layer 4 to be separated, on the other hand. Residues of the sacrificial layer 3 may be found on one and/or the other of the two parts. A finishing treatment may optionally be implemented in  
15 order to remove these residues.

Figure 5 illustrates the layer 4 transferred to the carrier 200.

#### Example n°1

This first example relates to a composite structure for the growth of a layer of graphene to be transferred to a carrier.

20 The composite structure comprises successively, with reference to figure 1B (it should be noted that not all of the layers shown in figure 1B are present in said structure):

- a substrate 1 of sapphire 500  $\mu\text{m}$  thick;
- a first thermal barrier layer 5 made of  $\text{SiO}_2$  500 nm thick;
- an optically absorbent layer 2 made of silicon carbide ( $\text{SiC}$ ) 30 nm thick;
- 25 - a sacrificial layer 3 made of silicon nitride ( $\text{Si}_3\text{N}_4$ ) 20 nm thick;
- a second thermal barrier layer 5 made of  $\text{SiO}_2$  1000 nm thick;
- a seed layer 8 of nickel 50 nm thick.

When said structure is subjected to a beam from a pulsed laser emitting at 193 nm, with a pulse duration of 20 ns and a fluence of approximately  $0.1 \text{ J.cm}^{-2}$ , through the  
30 substrate 1, the temperature within the structure increases over the duration of each pulse. The heat generated is mainly localized in the optically absorbent layer 2. When the temperature reaches the dissociation temperature of silicon nitride (i.e. around  $1900^\circ\text{C}$ ), part of the sacrificial layer, the second thermal barrier layer 5 and the seed layer 8 become detached from the substrate 1 and from the first thermal barrier layer 5.

35 After a laser pulse, the temperature homogenizes in the structure. Of particular interest is the temperature at the upper interface of the seed layer 8, that is to say the interface between the seed layer and the graphene layer.

Figure 6A shows the distribution of the temperature within the composite structure as a function of the depth  $z$  (in  $\mu\text{m}$ ) for different durations shorter than or equal to the laser pulse duration, which is 20 ns in this case.

Figure 6B shows the homogenization of the temperature within the structure as a function of the depth  $z$  (in  $\mu\text{m}$ ) for different durations after the end of the laser pulse.

Figure 6C shows the change in temperature  $T$  (in  $^{\circ}\text{C}$ ) at the seed layer as a function of time  $t$  (in ms). It can be seen that said temperature does not exceed  $275^{\circ}\text{C}$ , which is a much lower temperature than the temperature starting from which degradation of the electrical properties of graphene is observed.

At the wavelength of 193 nm, SiC exhibits an optical absorption coefficient more than three times higher than that of silicon nitride, while being stable above the dissociation temperature of silicon nitride.

The combination of an optically absorbent layer of SiC 30 nm thick and of a sacrificial layer of  $\text{Si}_3\text{N}_4$  20 nm thick advantageously replaces a single optically absorbent sacrificial layer of  $\text{Si}_3\text{N}_4$  100 nm thick used in the prior art.

Figure 7A thus presents the maximum temperature  $T$  at the upper interface of the seed layer 8 (in  $^{\circ}\text{C}$ ), for the combination of an optically absorbent layer of 30 nm of SiC and of a sacrificial layer of 20 nm of  $\text{Si}_3\text{N}_4$  according to the invention and for a single optically absorbent sacrificial layer of  $\text{Si}_3\text{N}_4$  100 nm thick, not in accordance with the invention, as a function of the laser pulse duration  $d$  (in ns). It can be seen that the maximum temperature is decreased by more than  $100^{\circ}\text{C}$  with the structure according to the invention.

Figure 7B illustrates the heat  $C$  required for detachment per unit area (in  $\text{J}\cdot\text{cm}^{-2}$ ) as a function of the laser pulse duration  $d$  (in ns), for the combination of an optically absorbent layer of 30 nm of SiC and of a sacrificial layer of 20 nm of  $\text{Si}_3\text{N}_4$  according to the invention and for a single optically absorbent sacrificial layer of  $\text{Si}_3\text{N}_4$  100 nm thick, not in accordance with the invention. It can be seen that the heat required is decreased by nearly  $0.02 \text{ J}\cdot\text{cm}^{-1}$  with the invention, i.e. a decrease of approximately 14%.

Furthermore, figure 7C illustrates results of numerical simulations for various composite structures.

The structures S1, S2 and S3 are in accordance with the invention. They all successively comprise the substrate 1 of sapphire, the first thermal barrier layer 5 made of  $\text{SiO}_2$ , the optically absorbent layer 2 made of SiC, the sacrificial layer 3 made of  $\text{Si}_3\text{N}_4$ , the second thermal barrier layer 5 and a layer of nickel, constituting a seed layer for the graphene layer to be separated (unless otherwise indicated, the thickness of each of said layers is that mentioned above). The structures S1 and S2 further comprise a thermal inertia layer 7 made of polycrystalline silicon between the second thermal barrier

layer and the seed layer 8; in the case of the structure S1, the thickness of the layer 7 is 1000 nm; in the case of the structure S2, the thickness of the layer 7 is 500 nm.

The structure S4 is not in accordance with the invention: it comprises a single optically absorbent sacrificial layer of  $\text{Si}_3\text{N}_4$  100 nm thick between first and second thermal barrier layers which are identical to those of the structures S1 to S3.

It can be seen that the maximum temperature decreases with increasing thickness of the thermal inertia layer 7. Thus, for the structure S2, comprising a thermal inertia layer 7 that is 500 nm thick, the maximum temperature is lower than 200°C for a pulse of 20 ns. In this case, the thermal inertia film provides 43% of additional surface heat capacity (in  $\text{J.K}^{-1}.\text{m}^{-1}$ ) with respect to all of the layers 3, 5 and 8.

#### Example n°2

This second example relates to a composite structure allowing the deposition of a layer of PZT (lead zirconate titanate) on a silicon substrate followed by the transfer of said layer to a flexible carrier. Such a layer exhibits ferroelectric, piezoelectric and/or pyroelectric properties.

The composite structure comprises successively, with reference to figure 1B (not all of the layers shown in figure 1B necessarily being present in said structure):

- a substrate 1 of silicon 500  $\mu\text{m}$  thick;
- a first thermal barrier layer 5 made of  $\text{SiO}_2$  500 nm thick;
- an optically absorbent layer 2 made of molybdenum 100 nm thick;
- a sacrificial layer 3 made of titanium and indium oxide (ITO) 20 nm thick;
- a second thermal barrier layer 5 made of  $\text{SiO}_2$  500 nm thick;
- a layer 4 of PZT 1  $\mu\text{m}$  thick.

In order to obtain satisfactory properties, said layer 4 must be heated to 600°C.

After this step, a flexible carrier in the form of a polyimide film is bonded to the PZT layer in order to transfer said layer thereto. The maximum temperature that the polyimide film can withstand is between 200 and 400°C depending on the duration of application of the temperature.

To separate said composite structure, a  $\text{CO}_2$  laser emitting infrared, for example having a wavelength of 10.6  $\mu\text{m}$ , is used.

Figure 8A illustrates the maximum temperature (in °C) at the bonding interface as a function of the laser pulse duration (in ns), for different composite structures S5-S8.

The limit temperature of 200°C is exceeded if the pulse duration is longer than 50 ns.

If the power of the laser source is not sufficient, it is possible to provide a transfer with a longer pulse (100 ns for example) by increasing the thickness of the thermal barrier layers 5 and/or by inserting a heat distribution film 7 in order to increase the heat

capacity of the layers between the sacrificial layer 3 and the bonding interface between the layer 4 of PZT and the carrier.

The structures S5, S6, S7 and S8 are in accordance with the invention. They all successively comprise the substrate 1 of silicon, the first thermal barrier layer 5 made of SiO<sub>2</sub>, the optically absorbent layer 2 made of molybdenum, the sacrificial layer 3 made of ITO, the second thermal barrier layer 5 and a layer 4 of PZT of 1 µm, constituting the layer to be separated (unless otherwise indicated, the thickness of said layers is that mentioned above). The structures S5 and S6 further comprise a thermal inertia layer 7 made of polycrystalline silicon between the second thermal barrier layer and the seed layer 8; in the case of the structure S5, the thickness of the layer 7 is 1000 nm; in the case of the structure S6, the thickness of the layer 7 is 500 nm. In comparison with the structure S8, the second thermal barrier layer of the structure S7 is thicker (1000 nm instead of 500 nm).

Figure 8B illustrates the power density  $D$  of the laser (in  $W.m^{-2}$ ) to be transmitted through the silicon substrate in order to dissociate the sacrificial layer, as a function of the laser pulse duration (in ns), for the structures S5-S8 mentioned above. The points are substantially coincident for all of said structures.

Figure 9A shows the distribution of the temperature within the composite structure S5 as a function of the depth  $z$  (in µm) for different durations shorter than or equal to the laser pulse duration, which is 100 ns in this case.

Figure 9B shows the homogenization of the temperature within the structure S5 as a function of the depth  $z$  (in µm) for different durations after the end of the laser pulse.

Figure 9C shows the change in temperature  $T$  (in °C) at the upper interface of the PZT layer of the structure S5 as a function of time  $t$  (in µs). It can be seen that said temperature does not exceed 180°C, such that the polyimide carrier bonded to the PZT layer does not run the risk of being damaged during the separation method.

Of course, the examples described above are provided only by way of illustration and are not limiting.

## REFERENCES

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**CLAIMS**

1. A method for separating a composite structure that is dismantlable by means  
5 of a light flux, said method comprising:
- providing the dismantlable composite structure (100) comprising successively:
    - a substrate (1),
    - an optically absorbent layer (2) made of a material suitable for at least  
10 partially absorbing a light flux, the substrate being substantially transparent to said light flux,
    - a sacrificial layer (3) suitable for dissociating under the application of a temperature higher than a dissociation temperature, made of a material different from that of the optically absorbent layer (2),
    - 15 • at least one layer (4) to be separated,
  - applying a light flux through the substrate (1), said light flux being absorbed at least in part by the optically absorbent layer (2), so as to heat said optically absorbent layer,
  - heating the sacrificial layer (3) by thermal conduction from the optically  
20 absorbent layer (2), up to a temperature higher than or equal to the dissociation temperature,
  - dissociating the sacrificial layer (3) under the effect of said heating.
2. The method as claimed in claim 1, wherein the product of the thickness of  
25 the substrate (1) and of the coefficient of absorption of the light flux by the substrate is less than 0.1.
3. The method as claimed in claim 1 or claim 2, wherein the product of the  
30 thickness of the optically absorbent layer (2) and of the coefficient of absorption of the light flux by said layer is greater than 2.3.
4. The method as claimed in one of claims 1 to 3, wherein the light flux is applied in a pulsed manner.
5. The method as claimed in one of claims 1 to 4, wherein the wavelength of  
35 the light flux is between 100 and 12 000 nm.

6. The method as claimed in one of claims 1 to 5, comprising, before the application of said light flux, a step of bonding the composite structure (100) to a carrier (200), the dissociation of the sacrificial layer (3) leading to the transfer of the layer (4) to be separated to the carrier (200).

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7. The method as claimed in claim 6, wherein the carrier (200) comprises at least one of the following materials: a semiconductor material, such as silicon; a metal, such as copper; a polymer.

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8. The method as claimed in one of the preceding claims, wherein the sacrificial layer (3) is in contact with the optically absorbent layer (2).

9. The method as claimed in one of the preceding claims, wherein the sacrificial layer (3) is made of a material that is substantially transparent to said light flux.

15

10. The method as claimed in one of the preceding claims, wherein the structure further comprises a first thermal barrier layer (5) that is substantially transparent to said light flux, between the substrate (1) and the optically absorbent layer (2).

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11. The method as claimed in one of the preceding claims, wherein the structure further comprises a second thermal barrier layer (5) between the sacrificial layer and the layer to be separated.

25

12. The method as claimed in either of claims 10 and 11, wherein the first and/or the second thermal barrier layer (5) has a linear thermal conductivity coefficient of less than  $10 \text{ W m}^{-1} \text{ K}^{-1}$ .

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13. The method as claimed in one of claims 10 to 12, wherein the first and/or the second thermal barrier layer (5) comprises at least one of the following materials: silica ( $\text{SiO}_2$ ), alumina ( $\text{Al}_2\text{O}_3$ ).

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14. The method as claimed in one of the preceding claims, wherein the structure further comprises a first film (6) suitable for reflecting or absorbing the light flux, between the sacrificial layer (3) and the layer (4) to be separated.

15. The method as claimed in claim 14, wherein said first film (6) comprises at least one of the following materials: silicon, silica ( $\text{SiO}_2$ ), silicon carbide ( $\text{SiC}$ ), molybdenum, silicon nitride ( $\text{Si}_3\text{N}_4$ ).

5 16. The method as claimed in one of the preceding claims, wherein the structure further comprises, between the sacrificial layer (3) and the layer (4) to be separated, a second film (7) suitable for distributing the heat over the entire area of the structure (100).

10 17. The method as claimed in claim 16, wherein said second film (7) comprises at least one of the following materials: alumina ( $\text{Al}_2\text{O}_3$ ), silica ( $\text{SiO}_2$ ), polycrystalline aluminum nitride ( $\text{AlN}$ ), polycrystalline silicon.

15 18. The method as claimed in one of the preceding claims, wherein the substrate (1) comprises at least one of the following materials: sapphire, quartz.

19. The method as claimed in one of the preceding claims, wherein the optically absorbent layer (2) comprises at least one of the following materials: silicon nitride ( $\text{Si}_3\text{N}_4$ ), polycrystalline silicon, polycrystalline silicon carbide ( $\text{SiC}$ ).

20 20. The method as claimed in one of the preceding claims, wherein the sacrificial layer (3) comprises at least one of the following materials: silicon nitride ( $\text{Si}_3\text{N}_4$ ), polycrystalline aluminum nitride ( $\text{AlN}$ ), polycrystalline gallium nitride ( $\text{GaN}$ ), indium tin oxide (ITO).

25 21. The method as claimed in one of the preceding claims, wherein the layer (4) to be separated comprises at least one of the following materials: a metal, such as copper; a group IV material having a hexagonal crystal structure, such as graphene; a piezoelectric, ferromagnetic or ferroelectric material; a phase-change alloy, such as  $\text{GeSbTe}$ .

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