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A METHOD OF CUTTING AT LEAST ONE THIN LAYER FROM A SUBSTRATE OR INGOT, IN PARTICULAR OF SEMICONDUCTOR MATERIAL(S)

Field of the invention and state of the art

The invention relates to cutting at least one thin layer from a substrate or ingot, in particular of semiconductor material(s) for making an electronic or an optoelectronic or an optical component or sensor.

In numerous applications associated with the fields of microelectronics, optoelectronics, or sensors, a technological operation consisting in transferring a layer of one substrate onto another represents a key operation enabling numerous materials structures or specific components to be fabricated. The layer for transfer may or may not include components that are complete or in a partial state of completion.

One example of such applications consists in making silicon on insulator (SOI) substrates. Typically, the insulator used is SiO_2 of amorphous structure on which it is not possible to deposit silicon of monocrystalline quality. One category of techniques for making such structures relies on molecular adhesion techniques referred to as "wafer bonding". These techniques are known to the person skilled in the art and in particular they are described in the work "Semiconductor wafer bonding Science and Technology" by Q.Y. Tong and U. Gösele, a Wiley Interscience Publication, Johnson Wiley & Sons. Inc. As described in that work, using such techniques, two substrates (generally silicon substrates) are assembled together, one being intended to form the silicon on insulator layer (the "source" substrate), that is to be transferred onto the other substrate that thus becomes the new "support" substrate supporting said SOI layer. A layer of insulation, typically of SiO_2 is previously formed on at least one of the faces of the

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substrates prior to assembly, thus obtaining a buried insulator situated beneath the SOI layer.

Certain variants are known as "bonded SOI" (BSOI) or indeed "bond etch back SOI" (BESOI). In addition to molecular adhesion, these variants rely on physically removing a source substrate either by techniques of the polishing or mechanical lapping type and/or by techniques of the chemical etching type. Other variants rely in addition to molecular adhesion on separation by "cutting" along a zone of weakness, such as the methods described in documents US-A-5 374 564 (or EP-A-0 533 551), US-A-6 020 252 (or EP-A-0 807 970) (separation along an implanted zone) or indeed in document EP 0 925 888 (separation by breaking along a buried layer that has been made porous).

Those layer transfer techniques present a generic nature since they enable structures to be made that combine various types of material with one another, and that it is not possible to make otherwise, and in particular by deposition. Examples are monocrystalline silicon substrates on quartz, AsGa substrates on silicon, etc. ... .

The advantage of such methods having a buried fragile layer is to be able to make layers based on crystalline silicon (or on SiC, InP, AsGa, $LinbO_3$, $LiTaO_3$, ...) in a range of thicknesses that extends from a few tens of angstroms (Å) to a few micrometers (μm), with very good uniformity. Even greater thicknesses are also accessible.

In addition to making substrates, there are numerous other examples of applications in which layer transfer techniques can provide a suitable solution for integrating components or layers on a support that is ex ante unsuitable for making them. These layer transfer techniques are also very useful when it is desired to isolate a fine layer, with or without components, from

its initial substrate, e.g. by separating or eliminating said substrate.

By way of example, more and more components might need to be integrated on supports that are different from those which enabled them to be made. By way of example, mention can be made of components on substrates made of plastics or on substrates that are flexible. The term "components" is used to mean any microelectronic device, optoelectronic device, or sensor device (e.g. a chemical, mechanical, thermal, biological, or biochemical sensor device) that is fully or partially "processed", i.e. that has been made in full or in part. In order to integrate such components on flexible supports (incompatible with making them), it is possible to use a layer transfer method which is performed after the components have been made on a substrate which is compatible with making them.

Still in the same spirit, turning a fine layer over while transferring it to another support provides engineers with a degree of freedom that is precious for designing structures that would otherwise be impossible. Taking and turning over such thin films make it possible, for example, to make so-called "buried" structures such as buried capacitors for dynamic random access memories (DRAMs) where, contrary to the usual case, the capacitors are made first and then transferred onto another silicon substrate, after which the remainder of the circuits are fabricated on the new substrate. Another example lies with making double gate transistors. The first gate of a CMOS transistor is made using conventional technology on one substrate, and it is then turned over and transferred onto a second substrate where the second gate of the transistor is made and the transistor is finished, thus leaving the first gate buried within the structure (see for example K. Suzuki, T. Tanaka, Y. Tosaka, H. Horie, and T. Sugii, "High speed and low power n+-p+ double gate SOI CMOS", IEICE Trans. Electron., Vol. E78-C, 1995, pp. 360-367).

An identical situation is to be found for example in the field of applications associated with telecommunications and microwaves. Under such circumstances, it is preferable for components finally to be integrated on a support presenting high resistivity, typically several kilohm-centimeters (kΩ.cm) at least. However a highly resistive substrate is not necessarily available at the same cost and quality as the standard substrates that are usually used. With silicon, silicon wafers having a diameter of 200 millimeters (mm) and wafers having a diameter of 300 mm are available at standard resistivity, whereas for resistivities greater than 1 kΩ.cm availability is quite inadequate at 200 mm and non-existent at 300 mm. One solution consists in making the components on standard substrates and then in transferring them during the final stages to a fine layer containing components on an insulating substrate of the glass, quartz, sapphire, etc. ... type.

From a technical point of view, these transfer operations have the major advantage of decorrelating the properties of the layer in which the components are made from those of the final support layer, and consequently they are advantageous in many other circumstances.

Relating more specifically to layer transfer techniques based on breaking or separating along a zone of weakness ("weakness" to be understood broadly and from a mechanical point of view) or a zone predefined to originate separation selectively (e.g. separation by chemical etching), several techniques are known concerning the step or combination that gives rise to the cut.

For example, certain combinations are based more specifically on mechanical separation (high pressure water jet as in document EP 0 925 888). Certain techniques based on the so-called "lift-off" principle also enable a thin layer to be separated from the remainder of the initial support, without necessarily

consuming it. Those methods generally make use of chemical etching acting selectively on a buried intermediate layer, optionally associated with the application of mechanical forces. That type of method is in widespread use for transferring III-V elements on to various types of support (see C. Camperi et al. IEEE Transactions and Photonics Technology, Vol. 3, 12 (1991) 1123).

As another example, document EP 0 925 888 describes cutting by means of a fracture along a buried layer that is made porous by mechanical means represented by a jet of water under pressure applied in the vicinity of the zone to be cut. A jet of compressed air can also be used as described in document FR 2 796 491, or it is also possible to exert traction as in document WO 00/26000. It can also be appropriate to insert a blade.

Other examples rely on a zone of weakness obtained by implantation. A cut can be obtained along this zone of weakness, optionally by combining said implantation with the specific means for applying mechanical forces as mentioned above (or other such means) and/or chemical etching and/or heat treatments, etc. A few examples of such techniques are to be found in documents US-A-5 374 564 (or EP-A-0 533 551), US-A-6 020 252 (or EP-A-0 807 970), and WO 00/61841.

Numerous means can be adopted to trigger or assist cutting along a zone of weakness. The four documents US 6 020 252, US 6 013 563, EP 0 961 312, and EP 1 014 452 provide more explicit explanations of, for example, mechanical forces in tension, in shear, in twisting, heat treatments using a wide variety of hot or cold sources of heat (conventional ovens, light means, lasers, electromagnetic fields, electron beams, cryogenic fluids, etc.), laser ablation of an intermediate layer, etc. ... .

Technical problem and presentation of the invention

The layer transfer techniques mentioned in the introduction nevertheless present certain specific drawbacks.

Techniques based on thinning down (mechanically, chemically, etc. ...) suffer from the drawback of consuming and sacrificing a substrate, which is penalizing, economically speaking. Such thinning techniques are also often quite difficult and expensive to implement.

Combinations based on applying external mechanical stresses (shear, twisting, bending, tension, ...) suffer from the drawback of generally requiring adhesion (molecular or otherwise) that is sufficiently strong to avoid breaking under the stress needed for rupturing the weak zone. A method for obtaining such adhesion is not always available in certain manufacturing methods or applications which are subject to very severe specifications (e.g. impossible to heat, impossible to use specific solvents or other chemicals, impossible to apply traction to the structure because of the risk of destroying sensitive components, ...).

In certain applications, techniques based on annealing and other heat treatments come up against incompatibility with raising temperature, e.g. the temperature of the final support on which the layer is to be integrated. For example, the new support may not be capable of withstanding the temperatures required (this applies to plastics materials). By way of another example, the incompatibility can stem from a combination of materials, in particular because they have too great a difference in thermal expansion coefficients which would cause an assembly that is not sufficiently uniform to break during a temperature rise (this applies for example to a structure combining silicon and quartz).

Techniques based on chemical etching are aggressive and this can make them incompatible with the final

support on which the layer for transfer is to be integrated, or with components that might already be present on said layer.

Amongst other combinations, documents US 6 013 563 and EP 1 014 452 describe or mention techniques based on applying beams of light and/or electrons.

Document US 6 013 563 refers to applying a beam of photons and/or electrons in order to heat the structure.

Document EP 1 014 452 describes a method in which an arbitrary source of photons (X rays, UV light, visible light, infrared light, microwaves, lasers, etc. ...) is suitable for giving rise to separation. The implementation described when using a laser, for example, refers to laser ablation of said intermediate layer which leads the authors to prefer using laser pulses of relatively high power ("most preferably for energy densities lying in the range 100 millijoules per square centimeter (mJ/cm^3) and 500 mJ/cm^3") and of relatively long duration ("preferably for durations lying in the range 1 nanosecond (ns) to 1000 ns, and most preferably for durations lying in the range 10 ns to 100 ns"). The authors also state that that method of implementation requiring relatively large amounts of energy to be delivered in order to operate suffers from the drawback of possibly damaging the layer that is to be transferred.

An object of the invention is to provide a method of cutting along a zone of weakness which does not rely on raising temperature or on chemical etching or on decomposing said layer of weakness (whether by ablation or otherwise).

According to the invention, this is obtained by a method according to claim 1.

In the method, a layer of weakness is cleaved by injecting a pulse of energy into the substrate so as to generate a sound wave of amplitude suitable for causing cleavage to take place in said layer of weakness.

Such a method is also advantageously associated with the characteristics of claims 2 to 25

The invention also provides apparatus for implementing the method proposed, in the claim 26.

The apparatus is advantageously of the type specified in any one of claims 27 to 29.

Description of the figures

The characteristics and advantages of the invention appear better from the following description referring to the accompanying figures in which:

- Figure 1 is a section through the set of semiconductor and insulating substrates after implantation and bonding;
- Figure 2 shows the relationship for energy deposited in the material when the energy is deposited with a laser;
- Figure 3 shows the sound wave at a given instant in the form of a curve P(x);
- Figure 4 shows the sound wave behind the break in the form of the relationship P(x);
- Figure 5 shows apparatus for depositing energy by laser pulse; and
- Figure 6 shows apparatus for depositing energy when using an electron beam to heat the surface layer of the semiconductor substrate.

Detailed description of one or more implementations

In a preferred first implementation of the invention, the procedure is as follows. The starting material is a semiconductor wafer, e.g. of silicon (2) (see Figure 1) having a thickness of about 500 μm, which is polished on one of its faces (1), and protons are implanted in said face at an energy such that their penetration depth into the semiconductor is a little greater than the thickness λ of the thin layer of semiconductor that is to be made. For example, to make a

layer that is about 1 μm thick, protons are used at an energy of about 150 kiloelecton volts (keV).

Thereafter, the insulating substrate (4) is prepared, and in the example shown in Figure 1 this is a substrate of silicon covered in a layer of SiO_2 having a typical thickness of a few tenths of a micrometer.

Thereafter, the substrates (4 and 2) are bonded together by molecular adhesion using a method that is now well known (see for example the work "Semiconductor wafer bonding Science and Technology" by Q.Y. Tong and U. Gösele, a Wiley Interscience Publication, Johnson Wiley & Sons. Inc.).

This produces the block shown in Figure 1b. This block is then impulse heated from the free surface of the semiconductor wafer (2), i.e. the face (13) shown in Figure 1b. The purpose of the heating is to raise the pressure in the thickness ε_0 affected by the heating, with this being necessary in order to generate the sound wave that is to be used for breaking the implanted layer (7) weakened by implantation or by any other means. To heat the layer of thickness ε_0 beneath the surface (13), it is necessary to implement or come close to implementing "constant volume heating" conditions. Heating causes expansion, but this can occur only in the form of a sound wave propagating at the speed of sound. If the heating is performed in time $\underline{t}$ shorter than the time taken by the sound wave to pass through half the thickness of the heated layer (of thickness equal to ε_0), it will readily be understood that the center of this layer will not be able to expand throughout the duration of the heating. Heating is thus performed at "constant volume", providing the following relationship is complied with, where C is the speed of sound:

$$t < \frac{\varepsilon_0}{2C}$$

The orders of magnitude implied by this relationship are dominated by the need to implement a sound wave that is very short in three-dimensional space.

Specifically, it is deemed that this is satisfied when the duration of the energy pulse is less than or of the same order as the duration needed by a sound wave to pass through the thickness of the zone that absorbs the energy of said pulse, said pulse being of energy selected to cause cleavage to take place in said weak zone.

In order to ensure that the rupture mechanism is effective, it is necessary for ε_0 to be of the same order of magnitude as the thickness λ of the layer that is to be detached, which is of micrometer order. It is also known that in a semiconductor, e.g. silicon, the speed of sound is about 2×10^3 meters per second ($m.s^{-1}$). The above relationship thus indicates that the duration of the pulse must be of the same order as or shorter than 1 ns, and preferably less than 0.5 ns, which is extremely brief but which can be achieved using special lasers or electron beams.

Once the above conditions are satisfied, the amplitude ΔP of the sound wave in compression or in expansion can be expressed by the Grüneisen relation:

$$\Delta P = \frac{1}{2}\Gamma.\rho.\frac{dE}{dm}$$

where:

Γ is the Grüneisen constant which for silicon is about 1.5;

ρ is the density of the medium and is about 2.5×10^3 (S.I. units);

$\frac{dE}{dm}$ is the variation in the specific internal energy of the medium. It is equal to the impulse heating per unit mass.

By way of example, it is assumed that the impulse heating gives rise to a temperature rise $\Delta\theta$ = 75°C in silicon having specific heat of 0.75 joules per gram, which gives:

$$\frac{dE}{dm} = 5.62\times10^4 \text{ (S.I. units)}.$$

Feeding these values into the above equation, it is found that a typical pressure is 105 megapascals (MPa), or in other words 1.05 kilobars (kbar). It should be observed that this wave amplitude, when implemented in the form of expansion, is of the same order of magnitude as the cohesion strength of the material, and that it is therefore of a kind likely to break the layer weakened by ion implantation. Finally, it should be observed that such a high pressure is obtained merely by a modest temperature rise of 75°C at the point where the energy is deposited, and that as soon as this energy disperses into the thickness of the substrate, the temperature rise becomes less than 1°C. It is thus genuinely possible to speak of a "cold" method of delamination.

The sound waveform depends on how the deposited energy is distributed in the material. If it were possible to deposit the energy in zero time and if its distribution $\varepsilon(x)$ as a function of depth $\underline{x}$ in the semiconductor (2) were of exponential appearance as shown diagrammatically in Figure 2a, then at said instant the pressure would be P(x) as represented by the curve shown in Figure 2b. In reality, the distribution Po(x) is deformed by the prorogation of expansion throughout the duration of deposition (which is never instantaneous).

This initial pressure splits into two waves, one going rearwards (in the increasing $\underline{x}$ direction) and the other going in the opposite direction, reflecting on the free face, and then also travelling rearwards, but this time in the form of an expansion wave. Figure 3 shows the complete wave at a given instant during its

propagation through the medium (2). It will be observed that the total impulse, i.e. the area beneath the curve, is zero, which is necessary since the laser or electron beam responsible for the heating is of quasi-zero impulse. When the expansion wave reaches the implanted layer whose breaking stress is assumed to be T, then the wave as transmitted downstream is truncated, as shown in Figure 4. Thus, the impulse received by the layer (5) and by its support (4) is not zero, causing said mass to be ejected at low speed.

There follows an examination of how the face (13) is impulse heated. It is shown above that the heated thickness should be about 1 μm, corresponding to a mass of material of about 2.5×10^{-4} grams per square centimeter (g/cm^2). Thus, in order to achieve the above-mentioned impulse temperature rise of 75°C it is necessary for the energy density of the beam to be about 1.87×10^{-4} J/cm^2. This ideal energy is very weak. In order to separate a layer from a wafer of Ø 300 mm, it would suffice for the laser pulse or electron beam to have energy of 0.13 J (!).

In reality, it is necessary to use much higher energy because of the expansion which occurs while energy is being deposited and also because absorption does not take place in ideal manner, i.e. it includes a distribution tail which is ineffective in raising pressure. In practice, the energy needed to separate a wafer over Ø 300 mm is about 13 joules.

In order to deposit the required energy in the surface (13), it is possible either to use a very short pulse laser such as a yttrium aluminum garnet (YAG) laser, for example, using one or two stages of amplification and a Q-switched pilot with wavefront steeping by saturatable plates so as to achieve pulses of 0.1 ns to 1 ns duration. For higher energies per pulse, the final stages of amplification may be made of neodymium glass. A setup of the type shown in Figure 5

is then obtained. A system of lenses L1, L2 serves to apodize the beam (9) so that the energy density is completely uniform over the entire surface (13) whose diameter can be as great as 300 mm using present-day technology. Once the apparatus has been set up, the laser beam having a wavelength close to 1.06 μm must be coupled with the semiconductor constituting the substrate (2). When this semiconductor is made of silicon, if the 1.06 μm beam were to be used directly, then absorption would take place over a mean thickness of about 100 μm, which is much too great. In order to reduce the thickness of the energy deposition, it is necessary to increase the absorption of the medium (2). This can be done:

1) by doubling, tripling, quadrupling the frequency of the laser beam using the now well known techniques based on non-linear effect plates;

2) surface doping, e.g. by ionically implanting phosphorus or arsenic in order to reduce resistivity and thus increase absorption at the 1 μm wavelength;

3) depositing a thin absorbent layer on the face (13), e.g. a metal layer having at thickness of 1 μm.

To deposit the energy, it is also possible to use a pulsed electron beam (10, see Figure 6) obtained using a pulse diode (12). To ensure that penetration in (2) is of 1 μm order, the energy of the electrons needs to be limited to about 30 keV. For a surface of Ø 300 mm, in order to deposit energy of about 3 joules, and taking account of the better absorption by the medium (2), the current delivered to the diode should be 150 kiloamps (kA) which is achievable.

In another preferred implementation of the invention, given by way of non-limiting indication, energy is deposited by means of a 1.06 μm laser beam as described above directly into the implanted layer (7) where it is desired to fracture the semiconductor (2). The description relates to the case where the

semiconductor (2) is constituted by silicon. Given that silicon is rather transparent at the YAG wavelength, it is possible to reach the layer (7) in the center of the stack (2, 4) by illuminating either the face (13) or the opposite face. Advantage is taken of the implanted layer being naturally much more highly absorbent than the initial crystal, even when implantation is performed using protons. It is also possible to increase its absorption strongly by implanting ions of phosphorus or of arsenic or of any other suitable element. It should be observed that under such circumstances, the expansion wave created is about twice that obtained in the preceding case, other parameters remaining identical. Furthermore, implementation is simplified since it is no longer necessary to ensure that the layer where the energy is deposited is parallel with the implanted layer since they are now the same layer. This disposition also presents the advantage of not requiring the bonding operation whose traction strength must be very high. Each of the two portions that result from cleaving the implanted layer (7) receives a clean impulse. In other words, the bonded interface (3) is subjected only to a compression wave, providing the face opposite to the surface (13) has deposited thereon a mechanically matching medium enabling the compression sound wave to be received so that it does not reflect in expansion from said face. This damper can be constituted by a plate of silica having a thickness of 10 mm or 20 mm which is permanently or temporarily bonded to the face opposite to the face (13).

The invention can be used for industrial manufacture of a substrate of the SOI type.

CLAIMS

1/ A method of cutting at least one thin layer from a substrate or ingot forming element for an electronic or optoelectronic or optical component or sensor, the method being characterized in that the following steps are implemented:

· forming a weak zone in said element, the thickness of the weak zone corresponding to the thickness of the layer that is to be cut off; and

· injecting into said element a pulse of energy of duration shorter than or of the same order as the duration needed by a sound wave to pass through the thickness of the zone absorbing the energy of said pulse, said pulse being of an energy that is selected to cause cleavage to take place at said weak zone.

2/ A method according to claim 1, characterized in that the weak zone is a porous zone.

3/ A method according to claim 1, characterized in that the weak zone is formed by deposition.

4/ A method according to claim 1, characterized in that the weak zone is formed by implantation.

5/ A method according to claim 4, characterized in that the implantation is implantation of phosphorus and/or arsenic and/or protons and/or rare gases.

6/ A method according to any preceding claim, characterized in that the substrate or ingot forming element is made of semiconductor material(s) and/or $LiNbO_3$ and/or $LiTaO_3$ or of a composite material based on these materials.

7/ A method according to claim 6, characterized in that the substrate or ingot forming element is made of silicon

and/or SiC and/or GaAs and/or InP and/or GaN and/or SiGe and/or Ge and/or $LiNbO_3$ and/or $LiTaO_3$, or of a composite material based on these materials.

8/ A method according to any preceding claim, characterized in that after the weakening step, said element is bonded onto another support, the energy pulse being injected into the resulting block.

9/ A method according to claim 7, characterized in that the bonding is bonding of the molecular adhesion type or by means of an adhesive glue.

10/ A method according to claim 7 or claim 8, characterized in that the block resulting from said bonding includes a layer of SiO_2, of Si_3N_4, or a combination of these two materials.

11/ A method according to any preceding claim, characterized in that the energy pulse is deposited by means of a laser beam.

12/ A method according to any one of claims 1 to 10, characterized in that the energy pulse is deposited by means of a beam of electrons.

13/ A method according to any preceding claim, characterized in that the duration of a pulse is less than 1 ns.

14/ A method according to any preceding claim, characterized in that the pulse is a single pulse.

15/ A method according to any preceding claim, characterized in that the pulse is repeated a plurality of times.

16/ A method according to any preceding claim, characterized in that the energy pulse is deposited via a face that is perfectly polished.

17/ A method according to claim 4 taken on its own or in combination with any one of claims 5 to 16, characterized in that the energy pulse is deposited via the same face as that through which implantation takes place.

18/ A method according to any one of claims 1 to 13, characterized in that the energy pulse is deposited from the face opposite the face through which implantation is performed.

19/ A method according to any preceding claim, characterized in that the energy pulse is deposited by selective absorption directly on the weak zone or its vicinity.

20/ A method according to claim 19, characterized in that the selectively absorbent nature is obtained by doping.

21/ A method according to claim 19, characterized in that the selective absorption is performed in a metal layer.

22/ A method according to claim 21, characterized in that the selective absorption is obtained within a deposited layer.

23/ A method according to claim 21, characterized in that the selective absorption is obtained within a layer whose properties have been modified by implantation.

24/ A method according to any preceding claim, characterized in that the energy pulse is deposited after all or part of a component has been made.

25/ A method of making an electronic or optoelectronic or optical component or sensor, characterized in that it implements the method according to any preceding claim.

26/ Apparatus for implementing a method according to any preceding claim, characterized in that it comprises means suitable for generating an energy pulse of duration shorter than or of the same order as the duration needed to pass through the thickness of the zone absorbing the energy of said pulse.

27/ Apparatus according to claim 26, characterized in that said means comprise a YAG or a neodium-doped glass laser suitable for delivering pulses of a duration that is advantageously shorter than 1 nanosecond.

28/ Apparatus according to claim 26, characterized in that said means comprise laser or a sheet of solid lasers.

29/ Apparatus according to claim 26, characterized in that it includes a pulsed diode type pulse accelerator delivering a beam of electrons having a duration of nanosecond order.