Method and Device for Surface Treatment of Substrates

Specification

This invention relates to a method for surface treatment ~~according to Claim 1 or 8~~ as well as a corresponding device ~~according to Claim 10~~.

In the semiconductor industry, different bonding technologies have already been used for several years in order to connect substrates to one another. The connecting process is called bonding. A rough distinction is made between the temporary bonding method and the permanent bonding method.

In the temporary bonding method, a product substrate is bonded to a carrier substrate in such a way that after processing, it can be detached again. Using the temporary bonding method, it is possible to stabilize a product substrate mechanically. The mechanical stabilization ensures that the product substrate can be handled without curving, deforming, or breaking. Stabilizations by carrier substrates are primarily necessary during and after a back-thinning process. A back-thinning process makes it possible to reduce the product substrate thickness to a few micrometers.

In the permanent bonding method, two substrates are bonded to one another continuously, i.e., permanently. The permanent bonding of two substrates also makes it possible to produce multi-layer structures. These multi-layer structures can consist of the same or different materials. Different permanent bonding methods exist.

- Copper-copper
- Aluminum-aluminum
- Tungsten-tungsten
- Silicon-silicon
- Silicon oxide-silicon oxide

Some of the metals used in the semiconductor industry are oxygen-affine. Thus, under an oxygen-containing atmosphere, aluminum forms a relatively solid aluminum oxide. During bonding, such oxides have a negative effect on the bonding result, since they are trapped between the two materials that are to be bonded to one another. Under extreme conditions, such an oxide can completely prevent a bonding process; under the most optimal conditions, the oxide is trapped. A mechanical breaking of the oxide layer before the incorporation is also conceivable. The oxide is thermodynamically stable enough not to decompose or to go into solid solution. It remains as oxide in the bonding boundary surface and has a negative effect on the mechanical properties there. Similar problems arise for tungsten and/or copper bonds.

~~It is therefore the object~~Embodiments of this invention ~~to indicate~~ disclose a method and a device with which an optimal connection is achieved at the lowest possible temperature, in particular with the greatest possible purity at the bonding boundary surface.

~~This object is achieved with the features of Claims 1, 8 and 10. Advantageous further developments of the invention are indicated in the subclaims.~~

According to an aspect of the present invention, there is provided a method for surface treatment of an at least primarily crystalline substrate surface of a substrate such that by amorphization of the substrate surface without deposition of a material an amorphous

layer is formed for bonding at the substrate surface with a thickness d > 0 nm of the amorphous layer, wherein a gas and/or a gas mixture is ionized for the amorphization, wherein the amorphous layer results from a phase conversion of the substrate material.

Also, all combinations that consist of at least two of the features indicated in the specification, the claims and/or the figures fall within the scope of the invention. In the indicated ranges of values, values as boundary values that lie within the above-mentioned limits are also to be considered as disclosed and can be claimed in any combination.

~~The basic idea~~ Embodiments of this invention ~~is to produce an in particular primarily~~ disclose an amorphized layer with a defined thickness d at a substrate surface that is to be bonded. In this case, the amorphized layer can be applied to the substrate in particular by chemical and/or physical deposition processes, preferably sputtering, or can be produced directly from the substrate. ~~A main aspect~~ An embodiment of the invention consists in the fact, however, that the amorphized layer is not made by a material applied by means of physical and/or chemical processes but rather results from a phase conversion of the substrate material. As a result, the deposition of material that is in particular accidental or harmful can be completely eliminated. Hereinafter, therefore, primarily the second method is presented in detail.

~~The~~ Embodiments of the invention relates in particular to a method for permanent bonding of two substrates, of which at least one, preferably two, was/were treated before the bonding as described below. Surface areas, in particular a contact side (preferably over the entire surface) of the two substrates or of at least one of the two substrates, are amorphized before the bonding process. Hereinafter in the patent specification, the entire substrate surface is described as an amorphized surface area, although according to embodiments of the invention, the amorphization of surface areas, in particular separate from one another,

which are smaller than the substrate surface, is conceivable. By the amorphization, a nanometer-thick layer is produced, in which the atoms of at least one of the surfaces to be bonded (contact sides) are arranged randomly. This random arrangement results in a better bonding result, in particular in the case of comparatively low temperatures. To produce a bond according to embodiments of the invention, in particular a purification of the surfaces (at least the contact sides), in particular for releasing oxides, is performed. Purification and amorphization preferably occur simultaneously, even more preferably by the same treatment. ~~A significant aspect~~ Embodiments of the invention ~~according to the invention is in particular~~ disclose the use of low-energy particles, in particular ions, whose energy is comparatively low but is sufficient to produce the amorphization described according to embodiments of the invention.

The removal of oxide from the substrate surfaces is advantageous for an optimal bonding process and a substrate stack with correspondingly higher bonding strength. This applies in particular for all materials in which an oxygen-containing atmosphere forms an accidental native oxide. This does not necessarily apply for deliberately produced oxygen substrate surfaces such as, for example, for silicon oxide. In particular, oxides according to embodiments of the invention - preferably at least predominantly, even more preferably exclusively, harmful, unnecessary and/or native, in particular metal oxides - are removed. Preferably, the above-mentioned oxides are removed to a very large extent, in particular completely, before a bonding process in order not to be incorporated into the bonding boundary surface (contact surface of two substrates). An incorporation of such oxides would lead to a mechanical destabilization and to a very low bonding strength. The removal of the oxide is carried out by physical or chemical methods. In an ~~especially preferred~~ embodiment ~~according to~~ of the invention, the removal of the unwanted oxides is carried out with the

same unit by which the method according to embodiments of the invention is implemented. As a result, the following can be simultaneously performed, in particular under optimal circumstances:

- Oxide removal
- Surface smoothing
- Amorphization

In alternative embodiments ~~according to~~ of the invention, the oxide removal is not carried out in the same unit.

In this case, it must be ensured in particular that no renewed oxidation of the substrate surfaces occurs during transfer of the substrates between the two units.

In other words, ~~the idea according to~~ embodiments of the invention consists in particular in the increase in bonding strength between two substrate surfaces by amorphization. In this case, the amorphization solves several problems:

In the first place, the amorphization according to embodiments of the invention preferably precedes a purification of the substrate surface. In particular, purification of the substrate surface and amorphization are performed simultaneously, even more preferably by the same process.

In the second place, the amorphization according to embodiments of the invention produces a planarization of the substrate surface. In this case, the planarization takes place during the amorphization, in particular in addition by the action of a force that acts during the bonding process.

In the third place, a thermodynamically metastable state at the substrate surface (bonding boundary surface) is produced by the amorphization. In another process step (in particular after the surfaces to be bonded make contact), a (back) conversion of partial areas

of the amorphous layer into a crystalline state results in this metastable state. In the ideal case, a complete conversion of the amorphous layer is carried out. The resulting layer thickness after making contact and the subsequent heat treatment of the amorphous layer are in particular greater than zero.

One ~~idea according to~~ embodiment of the invention consists primarily in the production of the amorphous layer that consists of the existing basic material of the substrate, in particular by particle bombardment. Preferably, before the bonding of the substrates, no material is applied to the substrate surfaces to be bonded.

The method according to embodiments of the invention makes possible the production of a complete and/or full-surface, in particular mixed, contact of two substrate surfaces, of which at least one, preferably two, is/are amorphized according to embodiments of the invention. Contaminants, inclusions, voids and bubbles are completely avoided by the complete contact.

The method according to embodiments of the invention is used in particular for the production of a contact that is complete and/or full-surface and/or unmixed of two, preferably different, substrate surfaces. In particular, the following materials can be bonded to one another in any combination.

- Metals, in particular
    - Cu, Ag, Au, Al, Fe, Ni, Co, Pt, W, Cr, Pb, Ti, Te, Sn, Zn
- Alloys
- Semiconductors (with corresponding doping), in particular
    - Element semiconductors, in particular
        - Si, Ge, Se, Te, B, -Sn
    - Compound semiconductors, in particular

- GaAs, GaN, InP, InxGa1-xN, InSb, InAs, GaSb, AlN, InN, GaP, BeTe, ZnO, CuInGaSe2, ZnS, ZnSe, ZnTe, CdS, CdSe, CdTe, Hg(1-x)Cd(x)Te, BeSe, HgS, AlxGa1-xAs, GaS, GaSe, GaTe, InS, InSe, InTe, CuInSe2, CuInS2, CuInGaS2, SiC, SiGe

- Organic semiconductors, in particular
  - Flavanthrone, perinone, Alq3, perinone, tetracene, quinacridone, pentacene, phthalocyanines, polythiophenes, PTCDA, MePTCDI, acridone, indanthrone

The following material combinations according to embodiments of the invention are preferably used:

- GaN – Cu,
- GaAs – SiO2,
- Cu – Al.

Although ~~the~~ embodiments ~~according to~~ of the invention ~~is~~ are suitable primarily for connecting two substrate surfaces that are made of different materials, hereinafter in the patent, reference is made primarily to the connection of two substrate surfaces of the same type for the sake of simplicity. In other words, embodiments of the invention relates in particular to a method for direct bonding. In this case, embodiments of the invention ~~is~~ are preferably based on the idea of amorphizing at least one surface (arranged in particular on the contact side) of a substrate before the bonding process. The amorphization is preferably carried out not by the deposition of a material that is amorphously resublimated respectively condensed under the given deposition parameters at the substrate surface but rather in particular by an alteration, primary forming and/or phase conversion of an amorphous layer at the substrate surface. This is done in particular by the introduction of kinetic energy by

particle bombardment, in particular ion bombardment, most preferably by a low-energy ion bombardment.

Amorphization

The amorphization is defined as the random arrangement of atoms in contrast to the well-defined arrangement of atoms in a crystal. The atoms can be the atoms of a one-atomic single-component system, a multi-atomic single-component system, a one-atomic multi-component system or a multi-atomic multi-component system. Component is defined as an independently variable material component of a phase. The amorphous phase has in particular no short-range order and/or no long-range order. An at least partially amorphous structure of the amorphous layer that is designed according to embodiments of the invention is defined as a phase batch, which consists of at least one amorphous phase and a crystalline phase. Reference is to be made to the volume ratio between the amorphous phase and the total volume as the degree of amorphization. According to embodiments of the invention, the degree of amorphization is in particular greater than 10%, preferably greater than 25%, even more preferably greater than 50%, most preferably greater than 75%, and all the more preferably greater than 99%.

The amorphization according to embodiments of the invention is limited in particular to the area that is near the surface of the substrates that are to be bonded to one another, preferably by selection of the process parameters temperature, pressure, ionization energy and/or ion current density during the amorphization. In particular, the material of the substrate, in this case apart from the amorphized layer according to embodiments of the invention, remains at least primarily, preferably completely, crystalline.

In ~~a first~~ an embodiment ~~according to~~ of the invention, only the substrate surface of a first substrate is amorphized. The thickness d of the amorphous layer immediately after the production according to embodiments of the invention in a substrate surface is in particular less than 100 nm, preferably less than 50 nm, more preferably less than 10 nm, most preferably less than 5 nm, and all the more preferably less than 2 nm.

In accordance with a further ~~development according to~~ embodiment of the invention, the substrate surface of a first substrate and the substrate surface of a second substrate are amorphized. In ~~a special~~ another embodiment ~~according to~~ of the invention, the amorphization of two substrate surfaces in the same unit is carried out in particular simultaneously in order to produce the same amorphous layers with the same process parameters. The amorphous layers that are produced preferably have the same thickness d_1 of the first amorphous layer of the first substrate and d_2 of the second amorphous layer of the second substrate. The ratio of the thicknesses d_1/d_2 of the two amorphous layers, in particular produced simultaneously, is $0.6 < d_1/d_2 < 1.4$, preferably $0.7 < d_1/d_2 < 1.3$, even more preferably $0.8 < d_1/d_2 < 1.2$, most preferably $0.9 < d_1/d_2 < 1.1$, and all the more preferably $0.99 < d_1/d_2 < 1.01$.

The substrate surfaces have a slight, but in particular not insignificant, roughness before, during and after the amorphization. In a preferred embodiment, the roughness of the substrate surface during the amorphization is reduced and has a minimum after the amorphization. The roughness is indicated either as a mean roughness, quadratic roughness or as an averaged depth of roughness. The determined values for the mean roughness, the quadratic roughness, and the averaged depth of roughness are different in general for the same measurement section or measurement surface, but lie in the same order of magnitude range. A measurement of the surface roughness is done with one of the measuring devices

(known to one skilled in the art), in particular with a profilometer and/or an atomic force microscope (AFM). In this case, the measuring surface is in particular 200 μm x 200 μm. Therefore, the following numerical value ranges for the roughness are defined either as values for the mean roughness, the quadratic roughness or for the averaged depth of roughness. According to embodiments of the invention, the roughness of the substrate surface before the amorphization is in particular less than 10 nm, preferably less than 8 nm, even more preferably less than 6 nm, most preferably less than 4 nm, and all the more preferably less than 1 nm. The roughness of the substrate surface after the amorphization is in particular less than 10 nm, preferably less than 8 nm, even more preferably less than 6 nm, most preferably less than 4 nm, and all the more preferably less than 1 nm.

The amorphization is preferably carried out by particle collision with the substrate surface. The particles are either charged particles or uncharged particles. The acceleration is preferably carried out with charged particles (ions) since charged particles can technically be accelerated more easily.

According to embodiments of the invention, the ions are preferably also used in the purification of the substrate surface. According to embodiments of the invention, therefore, in particular a purification of the substrate surface, in particular an oxide removal, is combined with the amorphization. If the substrates have been purified, in particular immediately before the amorphization, the method according to embodiments of the invention can, however, also be used exclusively for the production of the amorphous layer. The ratio between the entire surface F of the substrate and the purified surface f is referred to as a degree of purity r. Before the bonding process according to embodiments of the invention, the degree of purity is in particular to be greater than 0, preferably greater than

0.001, even more preferably greater than 0.01, most preferably greater than 0.1, and all the more preferably 1.

$$r = f / F$$

The purification and/or the amorphization preferably take place in a vacuum chamber as a process chamber. In this case, the vacuum chamber can be evacuated to be less than 1 bar, preferably less than 1 mbar, even more preferably less than 10^{-3} mbar, most preferably less than 10^{-5} mbar, and all the more preferably less than 10^{-8} mbar. In particular before the ions are used for amorphization, the vacuum chamber is evacuated preferably to a pre-established pressure, and is even more preferably completely evacuated. In particular, the proportion of oxygen in the process chamber is greatly reduced so that a renewed oxidation of the substrate surfaces is not possible.

According to embodiments of the invention, in particular the following gases and/or gas mixtures are ionized for the amorphization:

- Atomic gases, in particular
  - Ar, He, Ne, Kr,
- Molecular gases, in particular
  - H_2, N_2, CO, CO_2,
- Gas mixtures, in particular
  - Forming gas FG (argon + hydrogen) and/or
  - Forming gas RRG (hydrogen + argon) and/or
  - Forming gas NFG (argon + nitrogen) and/or
  - Hydrogen and/or

The gas mixtures used have in particular the following composition

Gas Mixture FG	Ar (%)	H (%)	Gas Mixture RFG	H (%)	Ar (%)	Gas Mixture NFG	Ar (%)	N2 (%)
FG 0	100	Atmosphere (10 sccm)	RFG 0	100	Atmosphere (10 sccm)	NFG 0	100	Atmosphere (10 sccm)
FG 1	96	4	RFG 1	100	0	NFG 1	95	5
FG 2	90	10	RFG 2	95	5	NFG 2	90	10
FG 3	80	20	RFG 3	90	10	NFG 3	80	20
FG 4	70	30	RFG 4	70	30	NFG 4	70	30
FG 5	50	50	RFG 5	50	50	NFG 5	50	50

Table 1: The table shows a listing of three exemplary gas mixtures: FGx, RFGx, and NFGx with their respective proportions of argon and hydrogen, or argon and nitrogen.

The ions are produced in an ionization process. The ionization process preferably takes place in an ion chamber. The ions that are produced leave the ion chamber and are preferably accelerated by an electric field and/or a magnetic field. Also, a deflection of the ions by electric and/or magnetic fields is conceivable. The ions strike the substrate surface in an ion beam. The ion beam is distinguished by a mean ion density.

According to an embodiment of the invention, the angle of incidence between the substrate surface and the ion beam can be freely selected and set. The angle of incidence is defined as the angle between the substrate surface and the ion beam. ~~The~~ In an embodiment, the angle of incidence lies in particular between 0° and 90°, preferably between 25° and 90°, even more preferably between 50° and 90°, most preferably between 75° and 90°, and all the more preferably at exactly 90°. The impact energy of the ions on the substrate surface can be controlled by the angle of incidence of the ion beam.

The amorphization can be controlled by the impact energy. In addition, the removal of contaminants, in particular oxides, can be controlled by the angle of incidence (and the associated impact energy of the ions on the substrate surface). In addition, the exact selection of the angle of incidence makes possible the control of the removal rate and thus the surface roughness. The angle of incidence is therefore selected in particular so that

amorphization, removal of contaminants, in particular oxides, and surface smoothing are maximized for the desired result. Maximization is defined in particular as a complete removal of contaminants, in particular oxides, a still further, in particular complete, smoothing of the surface (i.e., a reduction of the roughness value to zero), as well as an optimal, in particular thick, amorphized layer.

The control of the amorphization is implemented according to another embodiment of the invention by setting the kinetic energy of the accelerated particles, in particular ions. In an embodiment, ~~The~~ the kinetic energy of the particles is set in particular to be between 1 eV and 1,000 keV, preferably between 1 eV and 100 keV, even more preferably between 1 eV and 10 keV, most preferably between 1 eV and 1 keV, and all the more preferably between 1 eV and 200 eV.

The current density (the number of particles, in particular ions, per unit of time and area) is selected in particular to be between 0.1 mA/cm^2 and 1,000 mA/cm^2, preferably between 1.0 mA/cm^2 and 500 mA/cm^2, even more preferably between 50 mA/cm^2 and 100 mA/cm^2, most preferably between 70 mA/cm^2 and 80 mA/cm^2, and all the more preferably 75 mA/cm^2.

The treatment time is selected in particular to be between 1 s and 200 s, preferably between 10 s and 200 s, even more preferably between 50 s and 200 s, and most preferably between 100 s and 200 s.

Bonding

The bonding is done in particular in a separate bonding chamber, whereby the bonding chamber, preferably in a cluster unit, is connected integrally to the process chamber

for amorphization, even more preferably with a steadily maintained evacuation, and can be moved from the process chamber into the bonding chamber.

After the amorphization according to embodiments of the invention of at least one of the two substrate surfaces, in particular an alignment of the two substrates to one another is implemented. The alignment is preferably implemented by alignment units (English: aligners) and based on alignment marks.

After the two substrates are aligned with respect to one another, in particular contact is made. The contact is preferably begun in the center and is continued radially outward until the contact is complete. With this type of contact, a displacement of gases is ensured. In addition, the two substrates are bonded to one another with as little distortion as possible.

The contact preferably produces a prefixing, in particular a prebonding. The prebonding is distinguished by a binding strength of between 0.01 J/m^2 and 2.5 J/m^2, preferably between 0.1 J/m^2 and 2 J/m^2, even more preferably between 0.5 J/m^2 and 1.5 J/m^2, and most preferably between 0.8 J/m^2 and 1.2 J/m^2. The prebonding does not necessarily lead to a complete contact of the two substrate surfaces.

In another step according to embodiments of the invention, the actual bonding process of the pre-bonded substrates is carried out. The actual bonding process consists in particular of the action of a force and/or temperature. The bonding temperature according to embodiments of the invention is in particular less than 200°C, preferably less than 150°C, even more preferably less than 100°C, most preferably less than 100°C, and all the more preferably less than 50°C. The bonding force according to embodiments of the invention is in particular greater than 0.01 kN, preferably greater than 0.1 kN, even more preferably greater than 1 kN, most preferably greater than 10 kN, and all the more preferably greater

than 100 kN. The corresponding pressure areas are produced by standardizing the bonding force according to embodiments of the invention on the surface of the substrates. The substrates can have any shape. In particular, the substrates are round and are characterized across the diameter according to the industry standard. The substrates can have any shape but are preferably circular. For substrates, in particular the so-called wafers, the industry-standard diameters are 1 inch, 2 inches, 3 inches, 4 inches, 5 inches, 6 inches, 8 inches, 12 inches and 18 inches. In principle, however, the embodiment ~~according to~~ of the invention can handle any substrate, independently of its diameter.

According to embodiments of the invention, pressure loading causes the substrate surfaces to approach each other in the boundary layer (formed along the contact surface of the substrate surfaces) at which no contact is yet made by the prebonding. The approach of the substrate surfaces results in a continuous reduction in size and an ultimate closure of cavities. According to embodiments of the invention, in this case, the amorphization plays a decisive role, since a surface-isotropic electrostatic attraction is created by the amorphous state. Since the amorphous layers of the substrate surfaces that make contact with one another are both not crystalline, it is not necessary to take into account a suitable contact that continues onto the crystal lattice. The contact of two substrate surfaces with amorphous layers thus results in producing a new, larger, amorphous layer. The transition is configured in a flowing manner and is characterized according to embodiments of the invention primarily by the complete disappearance of a boundary layer.

The thickness of the entire bonded amorphous layer, in particular immediately after the bonding process according to embodiments of the invention, is in particular less than 100

nm, preferably less than 50 nm, even more preferably less than 10 nm, most preferably less than 5 nm, and all the more preferably less than 2 nm.

The bonding strength is influenced in particular by three decisive parameters, namely

- The thickness of the amorphous layer,
- The roughness,
- The number of incorporated ions that have a negative effect, and
- The bonding force.

According to embodiments of the invention, the bonding strength in particular increases with increasing thickness of the amorphous layer. The thicker the amorphous layer, the larger the number of randomly arranged atoms. The randomly arranged atoms are not subject to any long-range and/or short-range parameters, and the cavities are correspondingly easily filled by the above-mentioned processes, in particular diffusion and approach by pressure loading, since they do not have to be adapted to a regulated lattice. The contact surface and thus the bonding strength are increased by the filling. The increase of the contact surface is identified as a decisive parameter for the bonding strength. If the mean thickness of the amorphous layer is less than the mean roughness, not enough atoms of the amorphous phase are available to close the cavities. In contrast, it must be mentioned that a substrate surface with a very slight roughness also has correspondingly small cavities. That is to say, the slighter the roughness of a substrate surface, the smaller the thickness of the amorphous layer can also be in order to obtain a desired bonding result. A correspondingly thick amorphous layer is achieved according to embodiments of the

invention by a correspondingly high ionization energy, which results in the fact that the ions can penetrate as deeply as possible into the substrate.

The effects of the roughness are defined analogously. The greater the roughness, the more difficult the approach of the substrate surfaces is and the more energy the atoms of the amorphous substrate surfaces must expend in order to fill the cavities and thus to maximize the contact surface.

The bonding strength is also a function of the purity of the amorphous layer. Any stored atom or ion can lead in particular to destabilization, in particular reduction of the bonding strength. The ions that are used for amorphization can therefore also have a negative influence on the bonding strength, in particular if they remain in the amorphous layer after the amorphization. Therefore, in addition to a correspondingly low ionization energy, a lowest possible current density and treatment time are also desired.

If the current intensity is multiplied by the treatment time, the ions that strike the substrate surface within the treatment time per unit surface section are obtained. In order to minimize this number, the current density and/or the treatment time can be reduced. The fewer ions per unit surface strike the substrate surface, the fewer ions are incorporated in the amorphous layer. Primarily the particles that cannot enter into any bond with the material to be amorphized have negative effects on the bonding strength and are present only as defects, in particular point defects. These primarily include the noble gases, but also molecular gases.

In particular, according to embodiments of the invention, the use of gases or gas mixtures, whose ions are responsible for a reinforcement of the bonding interface, in

particular by forming new phases, is conceivable. A preferred option would be the use of ionized nitrogen, which nitrates the amorphous layer.

Analogous considerations apply for all other types of elements that form a compound, in particular a metal, covalent or ionic bond with the material of the amorphous layer. In order to be able to reduce the current density, in particular substrate surfaces that already have a minimal roughness are preferred. The smoother the substrate surface, the fewer and less energetic ions are required according to embodiments of the invention for the reduction of roughness. As a result, a reduction of the ionization energy and/or the ion stream and thus the number of ions per unit surface is made possible, which in turn leads to a lower number of incorporated ions and consequently to fewer defects and ultimately to an increased bonding strength.

Bonding strength is a function of bonding force, since a higher bonding force leads to a greater approach of the substrate surfaces and thus to a better contact surface. The higher the bonding force, the more easily the substrate surfaces approach one another, and the cavities are thus closed by locally deformed areas.

Heat Treatment

A heat treatment, which is separate in particular from the amorphization process, is carried out in particular either during and/or after the bonding in the bonder or after the bonding in an external heat treatment module (in particular integrated into the cluster). The heat treatment module can be a hot plate, a heating tower, a furnace, in particular a continuous furnace or any other type of heat-generating device.

The heat treatment takes place in particular at temperatures of less than 500°C, preferably less than 400°C, even more preferably less than 300°C, most preferably less than 200°C, and all the more preferably less than 100°C.

The time period of the heat treatment is selected in particular in such a way that after the heat treatment, the thickness of the amorphous residual layer according to embodiments of the invention is less than 50 nm, preferably less than 25 nm, even more preferably less than 15 nm, most preferably less than 10 nm, and all the more preferably less than 5 nm. The residual layer thickness never completely disappears, in particular in most cases studied, since complete conversion of the amorphous layer is possible only with a complete adaptation of the converted crystal lattice of the two substrate surfaces. Since a complete adaptation is rather unlikely for reasons of energy and geometry, a residual layer thickness that is different from zero remains in most cases that are described according to embodiments of the invention.

In particular, during and/or after bonding and/or in the case of heat treatment, a phase conversion from the amorphous state into the crystalline state is implemented.

In ~~a quite preferred~~ an embodiment ~~according to~~ of the invention, the above-mentioned process parameters are selected in such a way that a complete conversion of the amorphous layer into the crystalline phase is carried out.

According to embodiments of the invention, the purity of the converted material according to an advantageous embodiment is selected in percent by mass (m%) in particular to be greater than 95 m%, preferably greater than 99 m%, even more preferably greater than 99.9 m%, most preferably greater than 99.99 m%, and all the more preferably greater than