

Method and Device for Surface Treatment of Substrates

This invention relates to a method for surface treatment of a substrate surface as well as a corresponding device.

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.

The permanent bonding method of the anodic bonding is used in order to connect ion-containing substrates permanently to one another. In most cases, one of the two substrates is a glass substrate. The second substrate is preferably a silicon substrate. In the method, an electric field is applied along the two substrates that are to be bonded to one

another. The electric field is produced between two electrodes, which preferably bring the two surfaces of the substrates into contact. The electric field produces an ion transport in the glass substrate and forms a space charge zone between the two substrates. The space charge zone produces a strong attraction of the surfaces of the two substrates, which ensure contact with one another after the approach and thus form a permanent connection. The bonding method is thus based primarily on the maximization of the contact surface of the two surfaces.

Another permanent bonding method is the eutectic bonding. During eutectic bonding, an alloy is produced with a eutectic concentration or is set during the bonding. By exceeding the eutectic temperature, the temperature at which the liquid phase is in equilibrium with the solid phases of the eutectic, the eutectic melts completely. The liquid phase of the eutectic concentration that is produced wets the surface of the areas that are still not liquefied. During the solidification process, the liquid phase solidifies to form the eutectic and forms the connecting layer between the two substrates.

Another permanent bonding method is the fusion bonding. In the case of fusion bonding, two flat, pure substrate surfaces are bonded to one another by making contact. In this case, the bonding process is divided into two steps. In a first step, the two substrates are brought into contact. In this case, the attachment of the two substrates is carried out primarily by van der Waals forces. The attachment is referred to as a prebond. These forces make it possible to produce an attachment, which is strong enough to bond the substrates tightly to one another in such a way that a mutual shifting, in particular by the application of a shearing force, is possible only with a considerable expenditure of energy. In contrast, the two substrates, in particular by applying normal force, can be relatively easily separated from one another again. The normal forces in this case

preferably engage on the edge in order to produce a wedging action in the boundary surface of the two substrates, which produces a continuous crack and thus separates the two substrates from one another again. In order to produce a permanent fusion bond, the substrate stacks are subjected to a heat treatment. The heat treatment results in forming covalent connections between the surfaces of the two substrates. Such a permanent bond that is produced is only possible by the use of a correspondingly high force that in most cases accompanies a destruction of the substrates.

The publication US5441776 describes a method for bonding a first electrode to a hydrogenated, amorphous silicon layer. This amorphous silicon layer is deposited by deposition processes on the surface of a substrate.

The publication US7462552B2 shows a method in which a chemical gas phase deposition (English: Chemical Vapor Deposition, CVD) is used in order to deposit an amorphous silicon layer at the surface of a substrate. The amorphous layer has a thickness of between 0.5 and 10 μm .

In their publication US7550366B2, Suga et al. report on an accidentally produced amorphous layer, which is approximately 100 nm thick. This amorphous layer is located between the two substrate surfaces, which were prepared by a surface-activation process. The amorphous layer is a by-product of the ion bombardment of the substrate surface with inert gas atoms and metal atoms. The actual bonding process thus takes place between iron atoms, which cover the amorphous layer.

The heat treatment represents another technical problem. The bonded substrates have very often already been provided with functional units, such as, for example, microchips, MEMs, sensors, and LEDs, which have a temperature sensitivity. In particular, microchips have a relatively strong doping. At elevated temperatures, the

doping elements have an elevated diffusivity, which can result in an undesirable, disadvantageous distribution of the dopings in the substrate. In addition, heat treatments are always associated with elevated temperatures and thus also with higher costs, with the production of thermal voltages, and with extended process times for heating and cooling. In addition, bonding is to be done at the lowest possible temperatures in order to prevent shifting of different substrate areas, which consist of different materials and thus in general also of different thermal expansion coefficients.

A plasma treatment for purification and activation of a substrate surface would be an option for bonding at relatively low temperatures. Such plasma methods do not work or work only very poorly, however, in the case of oxygen-affine surfaces, in particular in the case of metal surfaces. The oxygen-affine metals oxidize and in general form relatively stable oxides. The oxides are in turn an obstacle for the bonding process. Such metals can also be bonded to one another with relative difficulty by diffusion bonding. The bonding of plasma-activated, in particular monocrystalline, silicon, which forms a silicon dioxide layer, works very well, however. The silicon dioxide layer is extremely well suited for bonding. The above-mentioned negative effects of the oxides therefore do not necessarily relate to all classes of materials.

The literature contains several approaches that describe direct bonding at lower temperatures. One approach in PCT/EP2013/064239 consists in applying a sacrificial layer, which is dissolved in substrate material during and/or after the bonding process. Another approach in PCT/EP2011/064874 describes the production of a permanent connection by phase conversions. The above-mentioned publications relate in particular to metal surfaces, which are more likely bonded via a metal bond and not via covalent

bonds. In PCT/EP2014/056545, an optimized direct bonding process of silicon by a surface purification is described.

The surface roughness of the surfaces/contact surfaces to be bonded represents another problem. In particular, when removing oxides and contaminants from the surfaces of the substrates that are to be bonded with one another with known methods, frequently a higher level of roughness is produced. On the microscopic scale, this roughness prevents full contact between the two surfaces during the bonding process, which has an adverse effect on the effective bonding strength. The two substrate surfaces bond almost overwhelmingly on tangent surface maximum points. Therefore, in particular, a contrast exists between good purification and provision of a surface that is as ideal as possible.

In the semiconductor industry, in particular substances or materials of the same type are to be connected to one another. The type similarity ensures that the same physical and chemical properties are present across the connecting point. This is in particular important for connections, across which electrical current is to be conducted, which are to have a low tendency toward corrosion and/or the same mechanical properties. Among these substances of the same type, primarily the following are found:

- 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.

Embodiments of this invention 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.

According to a first aspect of the present invention, there is provided a device for surface treatment of a substrate surface of a substrate with: a process chamber for receiving the substrate, means for amorphization of the substrate surface with the formation of an amorphous layer at the substrate surface with a thickness $d > 0$ nm of the amorphous layer, and a bonding chamber, wherein the bonding chamber in a cluster unit is connected integrally to the process chamber, wherein process parameters are selected such that a complete conversion of the amorphous layer into the crystalline phase is carried out.

According to a second aspect of the present invention, there is provided a cluster unit, comprising the above device.

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

Claims:

1. A device for surface treatment of a substrate surface (1o) of a substrate (1) with:
 - a process chamber for receiving the substrate (1),
 - means for amorphization of the substrate surface (1o) with the formation of an amorphous layer (2, 2', 2'') at the substrate surface (1o) with a thickness $d > 0$ nm of the amorphous layer (2.2', 2''), and
 - a bonding chamber, wherein the bonding chamber in a cluster unit is connected integrally to the process chamber,
 - wherein process parameters are selected such that a complete conversion of the amorphous layer (2, 2', 2'') into the crystalline phase is carried out.
2. The device according to claim 1, wherein the substrate is amorphized up to a thickness $d < 100$ nm of the amorphous layer (2, 2', 2'').
3. The device according to claim 1, wherein the substrate is amorphized up to a thickness $d < 50$ nm of the amorphous layer (2, 2', 2'').
4. The device according to claim 1, wherein the substrate is amorphized up to a thickness $d < 10$ nm of the amorphous layer (2, 2', 2'').
5. The device according to claim 1, wherein the substrate is amorphized up to a thickness $d < 5$ nm of the amorphous layer (2, 2', 2'').
6. The device according to claim 1, wherein the substrate is amorphized up to a thickness $d < 2$ nm of the amorphous layer (2, 2', 2'').
7. The device according to one of the preceding claims, wherein the substrate is amorphized in such a way that the mean roughness of the substrate surface (1o, 1o') decreases to a mean roughness of less than 10 nm.

8. The device according to one of claims 1 to 6, wherein the substrate is amorphized in such a way that the mean roughness of the substrate surface (1o, 1o') decreases to a mean roughness of less than 8 nm.
9. The device according to one of claims 1 to 6, wherein the substrate is amorphized in such a way that the mean roughness of the substrate surface (1o, 1o') decreases to a mean roughness of less than 6 nm.
10. The device according to one of claims 1 to 6, wherein the substrate is amorphized in such a way that the mean roughness of the substrate surface (1o, 1o') decreases to a mean roughness of less than 4 nm.
11. The device according to one of claims 1 to 6, wherein the substrate is amorphized in such a way that the mean roughness of the substrate surface (1o, 1o') decreases to a mean roughness of less than 2 nm.
12. The device according to one of the preceding claims, wherein the substrate is amorphized by collision of particles with the substrate surface (1o, 1o') with particles, wherein the angle of incidence between substrate surface (1o, 1o') and ion beam can be freely selected and set, wherein the angle of incidence lies between 75° and 90°.
13. The device according to one of claims 1-11, wherein the substrate is amorphized by collision of particles with the substrate surface (1o, 1o') with particles by acceleration of the particles, wherein the angle of incidence between substrate surface (1o, 1o') and ion beam can be freely selected and set, wherein the angle of incidence lies between 75° and 90°.
14. The device according to claim 12 or 13, wherein the particles are ions.
15. The device according to claim 12, 13 or 14, wherein the angle of incidence lies at 90°.

16. The device according to one of claims 12-15, wherein kinetic energy of the particles is set to be between 1 eV and 1,000 keV.
17. The device according to one of claims 12-15, wherein kinetic energy of the particles is set to be between 1 eV and 100 keV.
18. The device according to one of claims 12-15, wherein kinetic energy of the particles is set to be between 1 eV and 10 keV.
19. The device according to one of claims 12-15, wherein kinetic energy of the particles is set to be between 1 eV and 200 eV.
20. The device according to one of claims 12-16, wherein the current density of the particles is set to be between 0.1 mA/cm² and 1,000 mA/cm².
21. The device according to one of claims 12-16, wherein the current density of the particles is set to be between 1.0 mA/cm² and 500 mA/cm².
22. The device according to one of claims 12-16, wherein the current density of the particles is set to be between 50 mA/cm² and 100 mA/cm².
23. The device according to one of claims 12-16, wherein the current density of the particles is set to be between 70 mA/cm² and 80 mA/cm².
24. The device according to one of claims 12-16, wherein the current density of the particles is set to be 75 mA/cm².
25. The device according to one of the preceding claims, wherein the substrate is amorphized in a process chamber, which is evacuated before the amorphization to a pressure of less than 1 bar.

26. The device according to one of claims 1 to 24, wherein the substrate is amorphized in a process chamber, which is evacuated before the amorphization to a pressure of less than 10^{-3} bar.
27. The device according to one of claims 1 to 24, wherein the substrate is amorphized in a process chamber, which is evacuated before the amorphization to a pressure of less than 10^{-5} bar.
28. The device according to one of claims 1 to 24, wherein the substrate is amorphized in a process chamber, which is evacuated before the amorphization to a pressure of less than 10^{-7} bar.
29. The device according to one of claims 1 to 24, wherein the substrate is amorphized in a process chamber, which is evacuated before the amorphization to a pressure of less than 10^{-8} bar.
30. The device according to one of claims 1 to 29, wherein the bonding chamber in the cluster unit is connected with a steadily maintained evacuation in the process chamber.
31. The device according to one of the preceding claims, wherein the substrates are aligned after they are amorphized.
32. The device according to claim 31, wherein after the alignment a contact is made.
33. The device according to claim 32, wherein the contact begins in the center and is continued radially outward until the contact is complete.
34. The device according to claim 32 or 33, wherein the contact produces a prefixing with a binding strength of between 0.01 J/m^2 and 2.5 J/m^2 .

35. The device according to claim 32 or 33, wherein the contact produces a prefixing with a binding strength of between 0.1 J/m^2 and 2 J/m^2 .
36. The device according to claim 32 or 33, wherein the contact produces a prefixing with a binding strength of between 0.5 J/m^2 and 1.5 J/m^2 .
37. The device according to claim 32 or 33, wherein the contact produces a prefixing with a binding strength of between 0.8 J/m^2 and 1.2 J/m^2 .
38. The device according to one of the preceding claims, wherein the following gases and/or gas mixtures are ionized for the substrate to be amorphized:
- atomic gases,
 - molecular gases,
 - gas mixtures.
39. The device according to claim 38, wherein the atomic gases comprises Ar, He, Ne and/or Kr.
40. The device according to claim 37 or 38, wherein the molecular gases comprises H_2 , N_2 , CO and/or CO_2 .
41. The device according to claim 38, 39 or 40, wherein the gas mixtures comprises,
- Forming gas FG (argon + hydrogen) and/or
 - Forming gas RRG (hydrogen + argon) and/or
 - Forming gas NFG (argon + nitrogen) and/or
 - Hydrogen.
42. A cluster unit, comprising the device according to one of the preceding claims.