Method and Device for Permanent Bonding

Specification

The invention relates to a method for permanent bonding and a device for permanent bonding.

In the methods known under the name wafer bonding, two substrates, especially wafers, (in particular from the materials silicon, quartz or any other materials) are joined to one another. Here it is first of all distinguished between temporary bonding and permanent bonding. Temporary bonding is defined as all methods in which two substrates, in particular two wafers, are joined to one another such that the product substrate can be stabilized and processed without detaching from the carrier substrate, at the end of the process chain in any case it can be removed again from the carrier substrate in a controlled manner. In permanent bonding on the other hand, the two substrates, in particular wafers, are bonded to one another with the objective of producing a lasting connection which can no longer be broken.

The following enumeration outlines the possibilities of permanent bonding. In microsystem technology wafer bonding can be used for example to bond a wafer with cavities to a second wafer which is provided with micromechanical and microoptical components in order to protect them. Permanent bonding is also used to produce a permanent connection between silicon surfaces or silicon oxide surfaces in a so-called direct bond method. Furthermore, with the permanent bonding method of diffusion bonding or of eutectic bonding also innumerable metal surfaces can be permanently joined to one another. These metal surfaces need not be applied as blanket coating to the wafer, but can consist of several locally limited coatings which are distributed over the entire wafer. In particular these locally limited coatings which are distributed over the entire wafer can be surrounded by a dielectric material, in particular silicon dioxide. These surfaces are then called hybrid surfaces. The hybrid surfaces are aligned to one another and are bonded to one another in a permanent bond method such that the electrically conductive metal surfaces and the dielectric regions bond to one another. In this way stacking of several substrates with simultaneous production of an electrically conductive connection is enabled.

There are therefore different types of bonding methods which in addition to the actual bond method also differ by the different types of materials of the wafers which are to be joined. One

major disadvantage of currently used permanent bonding methods for metals consists in that the bond process leads to a satisfactory bond result only using very high heat supply and/or very high pressure. This very high thermal stress is also especially disadvantageous with respect to economical operation and is cost-intensive. Furthermore the construction and production of bonding systems which must apply corresponding high pressure in order to be able to bond wafers which are becoming larger and larger in a blanket and homogenous manner to one another are accordingly difficult. The production of corresponding bonding systems would fundamentally not be a problem if they could be built of any size. Bonding systems however must have certain dimensions which are stipulated by the semiconductor industry and must therefore be built to be correspondingly compact.

In addition to the indicated disadvantages of increased energy demand, substrate materials also react differently to increased heat supply, in which they have one thing in common. Heat supply always acts adversely on the substrate material used and can also lead to complete destruction of the substrate and in particular of the structures which are located on it.

According to a first aspect of the present invention, there is provided a method for permanent bonding of a first layer of a first substrate to second layer of a second substrate on a bond interface, characterized in that a dislocation density of a dislocation of the first and/or second layer is increased at least in the region of the bond interface before and/or during the bonding, wherein the substrate stack is mounted on a wafer chuck, wherein the wafer chuck allows a deformation of the first and/or second layer, wherein the wafer chuck and/or a pressure plate during pressure application on the entire surface of the substrate stack for bonding the layers is formed concave and/or convex, wherein the deformation of the wafer chuck and/or the pressure plate during the pressure application leads to the increase of the dislocation density of the dislocation at least in the region of the bond interface.

According to a second aspect of the present invention, there is provided a device for permanent bonding of a first layer of a first substrate to a second layer of a second substrate on a bond interface, with: a wafer chuck for receiving the first substrate, wherein the substrate stack can be mounted on the wafer chuck, wherein the wafer chuck allows a deformation of the first and/or second layer and a pressure plate for loading the substrate which is suitable for increasing the dislocation density of a dislocation of the first and/or second layer at least in the region of a bond interface, wherein the wafer chuck and/or the pressure plate can be formed concave and/or

convex during a pressure application on the entire surface of the substrate stack for bonding the layers, wherein the deformation of the wafer chuck and/or the pressure plate during the pressure application leads to the increase of the dislocation density of the dislocation at least in the region of the bond interface .

Embodiments of this invention disclose a method which makes it possible to implement a permanent connection of two substrate surfaces, in particular two metal surfaces as much as possible without the supply of heat, ideally at room temperature.

The surfaces of the substrates which are to be bonded to one another as per embodiments of the invention can consist of an electrically conductive, an electrically nonconductive material or can have hybrid properties. In particular, as per embodiments of the invention bond methods are defined as those which are used to join hybrid surfaces to one another. As already explained, they are defined as surfaces which consist of at least one conductive and one nonconductive material. According to the embodiments of the invention the conductive material is prepared for the bond process while the nonconductive surfaces can be bonded to one another according to known bond mechanisms. In order to illustrate the embodiments as claimed in the invention on embodiments as simple as possible, hereinafter preferably blanket metal surfaces which extend over the entire substrate are addressed. Furthermore the figures show solely blanket metal surfaces which extend over the entire substrate.

Embodiments of invention relate in particular to permanent Cu-Cu bonding. The method as per embodiments of the invention can fundamentally be applied to all other materials and material combinations in which by means of the embodiments of the invention at least one metastable state can be

produced which preferably leads to recrystallization of the structure. In addition to the bonding of only two substrates, there is often a desire to form substrate stacks which can be produced with the method as per embodiments of the invention. In the production of these substrate stacks it is necessary to define an optimized sequence of the joining with consideration of the type of material and of the existing cavities. Especially preferably the metastable state is produced by an increased dislocation density. The embodiments of the invention can be applied especially to the following:

- 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, preferably
    - Si, Ge, Se, Te, B, α-Sn,
    - compound semiconductors, preferably
        - GaAs, GaN, InP, $In_xGa_{1-x}N$, InSb, InAs, GaSb, AlN, InN, GaP, BeTe, ZnO, $CuInGaSe_2$, ZnS, ZnSe, ZnTe, CdS, CdSe, CdTe, Hg(1-x)Cd(x)Te, BeSe, HgS, $Al_xGa_{1-x}As$, GaS, GaSe, GaTe, InS, InSe, InTe, $CuInSe_2$, $CuInS_2$, $CuInGaS_2$, SiC, SiGe.

Mainly in the bonding of substrates with functional units such as for example microchips, memory chips, or MEMs, the bond process should advantageously be carried out at low temperatures in order to preclude or minimize damage to electronic components. Furthermore, low temperature methods for the most part also preclude damage by intrinsic thermal stresses due to the difference in the coefficients of thermal expansion of different materials.

In particular substrates, mainly substrates with functional components such as microchips, memory modules, MEMs, etc., are aligned to one another before the actual bond process. The alignment process in a bond process is of special importance since only correct alignment and contact-making ensure the functionality of the electronic components. In low temperature bonding of two wafers of different types of materials which have different coefficients of thermal expansion, alignment is greatly simplified since there is no temperature difference or only a very small one which leads to different expansion of the two substrates which consist in particular of different materials. The accuracy of alignment which is carried out at room temperature is therefore preserved in low temperature bonding or changes only very little. Factors which influence

alignment such as coefficients of thermal expansion can therefore be ignored for the most part. The use of such low temperatures has the disadvantage that bonding is much more difficult than in a bond process with higher temperatures (400°C).

Therefore embodiments of the invention disclose a method and a pertinent device which enables bonding of wafers even at low temperatures, preferably at room temperature.

The basic idea of embodiments of the invention is in particular to achieve recrystallization which spreads over the bond interface in the bonding, in particular Cu-Cu bonding. In the recrystallization grain growth and/or structure modification by regeneration of grains and extension of the newly formed grain boundaries occur. Recrystallization is therefore defined as a regeneration of the structure by regeneration of grains and/or grain growth. In the bonding of two substrates the regeneration of the structure takes place preferably beyond the bond interface so that a continuous structure arises between the two substrates which are to be bonded, in particular on the layers which have been deposited on the substrates.

Hereinafter it will no longer be distinguished between the substrate surfaces and the surfaces of the layers which have been deposited on the substrates. Both expressions can be used synonymously.

In particular the first and/or second layers can be components of the first and/or second substrate.

For recrystallization in materials, in particular metals, at moderate temperatures, as per embodiments of the invention materials can be provided with a high dislocation density, produced or chosen. The dislocation density is in particular greater than 10^7 cm^{-2}, preferably greater than 10^9 cm^{-2}, still more preferably greater than 10^{11} cm^{-2}, even more preferably greater than 10^{13} cm^{-2}, most preferably greater than 10^{15} cm^{-2}, most preferably of all greater than 10^{17} cm^{-2}. A dislocation is defined as a one-dimensional lattice defect which can arise either in the deposition of a material or which can be produced afterwards by plastic deformation in the crystal. A material with correspondingly high dislocation density is in particular in an at least metastable state and can be stopped by thermal activation from passing into a lower energy state by dislocation breakdown. The dislocation breakdown takes place preferably by recrystallization at higher temperatures and then results in a structure modification. A dislocation breakdown can as per embodiments of the invention take place alternatively at lower temperatures by annealing or crystal recovery. In a crystal recovery in any case the structure is not modified by recrystallization, but solely recombination of the dislocations

takes place. This process is not desirable as per embodiments of the invention and should be avoided.

The dislocation density is increased as per embodiments of the invention in which the dislocation is achieved both by individual pulse oscillations and/or continuing oscillations in the ultrasonic range. An individual pulse oscillation is defined in particular as one-time loading which will be detailed below. A continuing oscillation is defined in particular as several such loadings. Pulse oscillations cover in particular the entire bandwidth from high frequency to low frequency oscillations. The frequency of the oscillations as per embodiments of the invention is in particular between 1 Hz and 10^9 Hz, preferably between 10 Hz and 10^8, still more preferably between 100 Hz and 10^7, most preferably between 10^4 Hz and 10^6. Contact-making of the oscillating embodiments as claimed in the invention with the substrates to be bonded produces a high frequency, oscillating mechanical load which produces a corresponding dislocation density in the surfaces which are to be bonded, in particular the materials which have been deposited on the substrates. Contact-making of the two substrate surfaces with a pressure which is as low as possible and a temperature which is preferably as low as possible yields recrystallization of the structure in the bond process, in particular beyond the bond interface.

In order to be able to carry out recrystallization at temperatures which are as low as possible, not only the dislocation density, but also the purity of the recrystallizing material should be as high as possible. The purity is optimally indicated in percent by mass (m%) for technical purposes. The purity of the material is as per embodiments of the invention in particular greater than 95 m%, preferably greater than 99 m%, still more preferably greater than 99.9 m%, most preferably greater than 99.99 m%, most preferably of all greater than 99.999 m%.

The grain size of the recrystallizing structure before recrystallization is as per embodiments of the invention in particular less than 1000 nm, preferably less than 500 nm, still more preferably less than 100 nm, most preferably less than 50 nm, most preferably of all less than 10 nm. The grain size of the recrystallizing structure after recrystallization is in particular greater than 10 nm, preferably greater than 100 nm, still more preferably greater than 500 nm, most preferably greater than 500 nm, most preferably of all greater than 1000 nm. In one quite especially preferable embodiment the thickness of the grains which have been formed by recrystallization is the same size as the thickness of the recrystallized structure.

In order to increase the mobility of the atoms before and/or during and/or after the recrystallization, the structure preferably has a point defect density, in particular a vacancy density,

as large as possible. An increased number of vacancies improves the substitution diffusion and thus contributes to improved joining of the two surfaces which are to be bonded. The vacancy density is as per embodiments of the invention in particular greater than 10^{-12}, preferably greater than 10^{-10}, still more preferably greater than 10^{-8}, most preferably greater than 10^{-6}, most preferably of all greater than
10^{-4}. A vacancy density of roughly 10^{-4} already constitutes the typical boundary value of the vacancy density for metals in the vicinity of the melting point.

Moreover concave shaping of a wafer chuck or a bottom heater for heating the bottom of the substrate which allows bowing/sagging of the wafer in the micron range is conceivable. The concave shaping allows the bowing of the wafer. This bowing, in particular in high frequency stressing of the wafer, can produce additional stress loading and therefore advantageously an increase of the dislocation density in the wafer, in particular in a layer on the wafer. In particular the bowing of the wafer in the region of the wafer near the surface, which is located nearer the concave shaping, produces a tensile stress, while the surface of the wafer which is opposite the concave shaping, is loaded by compressive stress. The tensile or compressive stresses produced by the bending stress decrease in the direction of the neutral line. The maximum values of the tensile or compressive stress can be found in particular on the surfaces of the wafer. Due to the low thickness of the wafer the tensile or compressive stresses produced by bending are very small, but still can have a positive effect on the formation of the metastable state of one of the two layers as per embodiments of the invention.

The overall height of a compression apparatus for compressive loading of the substrate stack can be kept low in particular by using piezotechnology and integration into a device as per embodiments of the invention is thus not a problem. This method would, with regard to the adhesive capacity of the two bonded wafers to one another, approach approximately the currently known results of high temperature bonding with respect to the adhesive capacity.

One important advantage consists in that much lower thermal loading of the partially highly sensitive electronic components which are located on the wafers occurs during bonding and thus the probability of irreparable damage is for the most part precluded or greatly reduced. The lower bond temperature also yields a much lower energy consumption. Moreover low temperature bonding yields a higher throughput since time-consuming cooling of the bonded wafers can be omitted.

Embodiments of this invention show how it is possible to produce an increase in the dislocation density in micron-sized and/or nanometer-sized structures, in particular metals.

The dislocation density is increased as per embodiments of the invention mainly by means of ultrasound in the structure. The subject matter of embodiments of the invention is in particular a device which has at least one oscillating apparatus using which the structure of the regions which are to be bonded to one another can bring into a metastable energy state [sic] so that an improved bond action is achieved. In particular the embodiments increase the dislocation density in the regions of at least one of the two substrates. The embodiments can be applied to the substrate surfaces before and/or after the substrates make contact. Especially preferably the production of the dislocation density as per embodiments of the invention takes place only after the two substrates make contact with one another. But it is also conceivable as per embodiments of the invention to produce the dislocation density before contact-making or before and after contact-making.

The device preferably has a thermostat with which the device as per embodiments of the invention can be heated in a monitored manner and in which the bond temperature fluctuates more advantageously in a range from room temperature to distinctly below 300°C. The monitored heating can alternatively be undertaken by a control technology which depending on the substrate material takes into account in particular also other process-relevant parameters in the formulations which are to be used. Treatment of the substrates which have been bonded to one another in an independent external furnace separate from the embodiment as of the invention would also be conceivable. Especially preferably it would then be a continuous furnace.

The embodiments of the invention are preferably apparatus which are able to bring at least parts of a preferably entire substrate or a substrate stack which has already been joined to one another by a prebond into a metastable state by an oscillation. The oscillation can be an oscillation with a single period or several periods as per embodiments of the invention.

Especially preferably the dislocation generation and structure modification are initiated directly by the device as per embodiments of the invention during the bond process. This can prevent a metastable state which has been produced prior to the bond process from being degraded again by relaxation processes and from no longer being available during the bond process. Of course the production of a metastable state as per embodiments of the invention in at least one of the two substrates prior to the bond process and an additional second or subsequent generation or strengthening of a metastable state after contact-making, in particular during the bond process, are also conceivable. In particular, a friction welding process on the microlevel and/or nanolevel which is caused by

macroscopic delivery of a force could be involved.

In particular one embodiment of this invention consists in supporting the substrate stack on a wafer chuck which is made to allow oscillation and/or deformation of the first and/or second layer. This can take place in particular by locating bearings which are located in particular solely on the periphery of the wafer chuck and/or of the oscillating body for support of the wafer chuck and/or of the oscillating body.

Preferably the two substrates which are to be joined are aligned to one another within an alignment unit (alignment module). In one special alignment process the two substrates make contact with one another in particular from the centric middle of the substrates toward the radial periphery of the substrates.

Dislocations are preferably produced as per embodiments of the invention by delivery of mechanical shear stresses. These shear stresses are produced in the grains by stress loading which has been applied outside.

The dislocation density as per embodiments of the invention can be produced by each of the following embodiments of the invention either prior to contact-making, after contact-making, but prior to bonding or after contact-making during bonding.

In a first embodiment of the invention the dislocation density is produced by a locally concentrated oscillating element. In this embodiment the invention oscillations are produced by the oscillation element which stresses the substrate or substrate stack in particular in a locally limited manner. The oscillation element can be excited in particular either electrically, mechanically, pneumatically or hydraulically. Especially preferably it is an electrically excitable piezoelectric oscillation device. Moreover a possible spatial separation of the alignment module, oscillation apparatus and/or the bond chamber which is to be used for heating is also conceivable and claimed. But to the extent described a combination of the aforementioned apparatus with a cluster is expressly claimed. A sequence of the individual method steps is likewise claimed. In one quite especially preferred embodiment bonding of the two substrates by recrystallization at the sites which have already been stressed by the oscillation element takes place solely by the oscillation element. In another preferred embodiment the oscillation element increases only the dislocation density without leading to an immediate recrystallization and thus to immediate bonding. The actual bond process then takes place either in a furnace and/or in its own bond chamber in which the entire substrate stack can be again heated and/or exposed to pressure in a blanket manner.

In other embodiments of the invention the substrate or the substrate stack are set into oscillation in a blanket manner, especially into bending oscillation and/or heavy oscillation. The substrate or the substrate stack rests on a wafer chuck and is fixed, in particular compressively loaded by a pressure plate or a similar device as per embodiments of the invention on the side opposite the wafer chuck. Afterwards an especially local oscillating force or one which at least does not cover the entire surface of the substrate or substrate stack as per embodiments of the invention is applied. This application of force sets the entire substrate or the entire substrate stack into oscillations. In doing so the substrate holder and/or the pressure plate are in particular designed such as to be able to concomitantly oscillate themselves. Use of a stable and thick wafer chuck and a stable pressure plate in order to produce an oscillating shear stress on the substrate or the substrate stack would also be conceivable. Similar considerations also apply to torsional stress which in any case does not constitute the preferred embodiment due to the radial dependency of the deformation on the center of the substrate or of the substrate stack.

In another embodiment of the invention the generation of a metastable equilibrium, especially a dislocation-rich layer, is based on the use of a static wafer chuck and/or a static, nonplanar pressure plate. The wafer chuck and/or the pressure plate are preferably shaped concavely and/or convexly. In one special embodiment they are formed from an elastic material which in the unloaded state does have a planar surface, but can deform accordingly concavely and/or convexly under compressive loading. This shaping possibly likewise forces the substrate stack into a concave and/or convex shape; this leads to a corresponding stress on the substrate stack and thus on the surfaces which are to be bonded to one another. In particular, in contrast to the embodiments of the invention which were already named above, not dynamic, oscillating compressive stress, but a purely static, in particular blanket compressive stress on the substrate stack takes place.

In one quite special embodiment of the invention the elasticity of the wafer chuck is used to produce the aspect of the invention. The wafer chuck has a certain elasticity and is thus able to deform under compressive loading. The wafer chuck can fundamentally be shaped as desired, preferably convexly, concavely or in a planar manner. In this special embodiment mainly a planar wafer chuck is suitable. Therefore hereinafter reference is made to a planar wafer chuck. Slightly concave elastic deformation is effected by applying pressure to the elastically deformable wafer chuck which is planar however

prior to the elastic deformation. The wafer chuck is more strongly elastically deformed in the middle than on the edge. The maximum deformation in generally any direction, but in particular in the direction of the force, is in particular less than 1 mm, preferably less than 100 μm, still more preferably less than 10 μm, most preferably less than 1 μm, most preferably of all less than 100 nm. The modulus of elasticity of the material from which the wafer chuck is produced is in particular greater than 10 MPa, preferably greater than 100 MPa, still more preferably greater than 1 GPa, most preferably greater than 10 GPa, most preferably of all greater than 100 GPa. The inventive aspect of this embodiment consists in particular in applying a force, especially a surface force, to the substrate stack. The substrate stack is more or less forced into the wafer chuck which is minimally deformed, in particular concavely, by the elasticity of the wafer chuck. Due to this extremely slight bowing of the substrate stack the two surfaces of the two substrates which are not yet bonded to one another are slightly shifted laterally, in particular along their bond interface, to one another. The resulting friction between the two surfaces which are to be bonded to one another causes the generation of the metastable state, in particular of the dislocation-rich structure, as per embodiments of the invention. When the substrate stack is unloaded the elastic energy in the wafer chuck is used to transfer the wafer chuck as well as the substrate stack again into its initial shape. In doing so repeated friction which however acts in the opposite direction occurs in the substrate stack. This process can if necessary be repeated as often as wished.

In another embodiment of the invention, it is also conceivable to configure the compressive loading apparatus and/or the wafer chuck and/or the entire system in terms of construction technology such that a noteworthy bowing of the wafer chuck and thus also of the substrate stack to be stressed takes place only during loading. In particular this especially preferred embodiment is implemented such that the wafer chuck on its periphery is supported (preferably solely), in particular around the entire circumference, by a bearing, in particular a locating bearing, while the center is not supported or is only supported compliantly. In this special embodiment the wafer chuck and thus the substrate stack in the unloaded case, ignoring the effect of gravity and production tolerances, can be considered planar, bow concavely in the middle in any case under a load, preferably a spot load along the axis of symmetry of the pressure piston, still more preferably a surface load along the pressure plate.

One important embodiment of the invention is the generation of a metastable state, in particular of a structure with increased dislocation density in the surfaces of two surfaces which are

to be bonded to one another, by elastic deformation of the wafer chuck and by friction between the two surfaces which has been caused by it.

In order to apply the stresses mentioned in the preceding paragraph, supporting the substrate or the substrate stack on different wafer chucks is conceivable. The wafer chucks can be supported in a blanket manner or only on their periphery.

The amplitudes of the oscillation exciter are in particular smaller than 100 μm, preferably smaller than 1 μm, more preferably smaller than 100 nm, most preferably smaller than 10 nm.

The lateral displacements which are in particular parallel to the substrate surface and which are produced by the amplitudes can assume theoretically any values during the process as per embodiments of the invention as long as after completion of the process they assume a residual alignment fault which is smaller than 100 μm, preferably smaller than 1 μm, more preferably smaller than 100 nm, most preferably smaller than 10 nm. In particular the lateral displacements are set to be smaller than 10 μm, preferably smaller than 1 μm, more preferably smaller than 100 nm, most preferably smaller than 10 nm. The vertical displacements during the process as per embodiments of the invention are in particular smaller than 10 μm, preferably smaller than 1 μm, more preferably smaller than 100 nm, most preferably smaller than 10 nm.

As per embodiments of the invention at least one compressive prestress applied especially in a blanket manner to the substrate or substrate stack is produced. The compressive prestresses as per embodiments of the invention are in particular greater than 10 N/mm^2, preferably greater than 100 N/mm^2, more preferably greater than 200 N/mm^2, most preferably greater than 1000 N/mm^2.

The compressive prestress or the von-Mises comparison stress is as per embodiments of the invention in particular greater than the yield point of the material of the substrate or of the layer which is located on the substrate and which is to be used for bonding in order to support plastic deformation which additionally promotes the corresponding dislocation formation. The yield point of the material is preferably smaller than 5000 N/mm^2, preferably smaller than 1000 N/mm^2, still more preferably smaller than 750 N/mm^2, most preferably smaller than 500 N/mm^2, most preferably of all smaller than 300 N/mm^2. The tensile strength of the material is preferably smaller than 5000 N/mm^2, preferably smaller than 1000 N/mm^2, still more preferably smaller than 750 N/mm^2, most preferably smaller than 500 N/mm^2, most preferably of all smaller than 300 N/mm^2. Pure copper which has not been cold-deformed and which is therefore not yet work-hardened has for example a yield point of roughly 70 N/mm^2 and a tensile strength of roughly 200 N/mm^2.

Additional forces which can change over time are produced by superposition of the oscillating stress with the prestress. By the prestress, in particular beyond the yield point of the material, the latter is at least in the flow region of the material with a positive half-wave.

Another inventive effect which benefits the bond properties is the heat energy which has been delivered into the system by the devices as per embodiments of the invention and the temperature which can be reached with it. Mainly in the embodiment of a locally concentrated oscillation element as per embodiments of the invention can a very high heat density and thus a very high temperature be produced by which the bond process can be locally initiated. Further heat treatment can be especially advantageously omitted in this case. Recrystallization takes place preferably at a temperature as low as possible, as a result of which the temperature which can preferably be produced by the local oscillation element can be accordingly low. The temperature which has been produced by a locally concentrated oscillation element is in particular less than 800°C, preferably less than 600°C, still more preferably less than 400°C, most preferably less than 200°C, most preferably of all less than 50°C.

Regardless of the embodiment which has been used, the substrate stack after successful treatment can be heat-treated in an external furnace which is separate from the embodiment of the invention. Regardless of the aforementioned use of a separate furnace, the heat treatment is also possible in the bond chamber or in any other module which has been implemented in the process chain. In particular only by heat treatment does the predominant recrystallization of the structure and thus the actual permanent bond take place. Recrystallization takes place preferably at a temperature which is as low as possible. The temperature in the furnace or bonder is in particular less than 800°C, preferably less than 600°C, still more preferably less than 400°C, most preferably less than 200°C, most preferably of all less than 50°C.

Figure 1a shows a schematic cross section of a coated substrate and an enlargement of the microstructure of the coating,

Figure 1b shows a schematic cross section of a coated substrate and an enlargement of the microstructure of the coating after an increase of the dislocation density.

Figure 1c shows a schematic cross section of two coated substrates after the contact-making process and an enlargement of the microstructure of the coatings,

Figure 1d shows a schematic cross section of two coated substrates after a bond process and