A semiconductor wafer with a heteroepitaxial layer and a method for producing the wafer

A crystalline heteroepitaxial layer deposited on a single crystal substrate by epitaxial deposition typically differs from the substrate in several material properties including crystal lattice dimensions and thermal expansion coefficient. During the early stages of the deposition the heteroepitaxial layer is strained with respect to the underlying substrate lattice. After exceeding a certain layer thickness (critical thickness) the crystal of the heteroepitaxial layer starts to relax via the insertion of so called misfit dislocations (MFD). Although oriented in the plane perpendicular to the growth direction not all MFD extend to the edge of the substrate wafer but a certain number bends and forms threading dislocations (TD) propagating through the growing layer to the surface. TD forming clusters along lines are called pile-up-s (Pu) and are especially harmful for electronic devices. The stress fields from the dislocation network also cause a surface roughening called cross-hatch. The formation of MFD, Pu, TD, cross-hatch and a bending of the wafer (bow, warp) are mechanisms by which the strain from the lattice mismatch is relieved. Many epitaxial deposition techniques have been developed to reduce the negative effects of the strain relaxation on the crystal quality of the heteroepitaxial layer. SiGe deposition on Si is a well known system to increase the lattice constant from Si to pure Ge which has a lattice constant being 4.2 % larger than that of Si. Grading of the Ge concentration in the SiGe layer has been a successful way to reduce the density of TD and Pu and the surface roughness of SiGe buffer layers. Many variations of grading the Ge concentration to match the crystal lattice of Si to the intended crystal lattice constant at the surface of the graded $Si_{(1-x)}Ge_x$ buffer layer have been developed.

So far little attention has been given to the reactions after the deposition has ended. Typically the deposition is done by heating the substrate, e.g. a silicon wafer, to a certain temperature and then providing the components for growing a film in the gas phase (CVD, PVD, MBE etc.). When the film growth ends the film is fully or partially relaxed with regard to the substrate. Sometimes annealing steps are applied to fully relax the SiGe buffer. After the deposition is completed the cooling of the layered wafer starts. Because of the difference in thermal expansion coefficient between heteroepitaxial layer and substrate a stress is generated and the wafer bends to a certain degree resulting in a curvature of the wafer. The bowing of the wafer is a function of the film stress, the thickness of the film and the mechanical properties of the substrate. Attempts have been made to minimize the bow of the resulting SiGe/Si structure like limiting the thickness of the heteroepitaxial layer.

US2008/0017952 A1, which is entirely included by reference herewith, describes a method to reduce bow caused by relaxed SiGe buffer layers by means of inserting thin strained transitional layers of silicon into the growing SiGe layer. These layers are claimed to reduce bow to a certain extent and the density of TD to less than 10^4 cm^{-2}. Although this approach has some positive effect on bow, it fails in regard of reducing cross-hatch and surface-roughening.

It is the object of the present invention to provide an appropriate solution for the reduction not only of bow and the density of TD but in particular also a reduction of cross-hatch and surface-roughening.

The invention provides a semiconductor wafer comprising a substrate having a first side and a second side; a fully or partially relaxed heteroepitaxial layer deposited on the first side of the substrate; and a stress compensating layer deposited on the second side of the substrate.

The invention further provides a method for producing a semiconductor wafer comprising depositing on a first side of a substrate a fully or partially relaxed heteroepitaxial layer at a deposition temperature; and before cooling the wafer from the deposition temperature, providing a stress compensating layer (SCL) on a second side of the substrate.

The claimed method comprises providing a stress compensating layer on the backside of the substrate wafer before the wafer is cooled from a deposition temperature after the deposition of

a fully or partially relaxed buffer layer (hereinafter called "heteroepitaxial layer") on the front side of the wafer. The SCL is advantageously grown in a way to provide an appropriate amount of stress for compensating the stress generated by the heteroepitaxial layer during the wafer is cooled down from the deposition temperature. An appropriate amount of compensating stress is achieved according to one embodiment of the invention, if the thickness and the composition of the stress compensating layer corresponds to or is similar to the thickness of the heteroepitaxial layer. Similar composition means that the concentration of a component does not differ more than about 20 % in the heteroepitaxial layer and the stress compensating layer. Similar thickness means that the thickness of both layers does not differ more than 20 %. An appropriate amount of compensating stress is achieved according to another embodiment of the invention, if the compensating stress layer comprises a constant composition SiGe layer and either the thickness or the composition of the constant composition SiGe layer or both are used for stress control. In principle, this approach is independent of the composition and thickness of the heteroepitaxial layer. Increasing the thickness of the constant composition SiGe layer or increasing the concentration of Ge in the constant composition SiGe layer or increasing both will increase the stress for compensating the stress caused by the heteroepitaxial layer during the cooling. The concentration of Ge in the constant composition SiGe layer is preferably chosen within a range of from 10 to 80 %.

It was unexpected that, by providing a stress compensating layer in accordance with the present invention, not only the bow of the resulting wafer can be properly controlled but also cross-hatch and surface-roughness of the heteroepitaxial layer can be significantly reduced.

The inventors of the present invention conjecture that the provision of the stress compensating layer prevents a degradation of the heteroepitaxial layer during the phase after cooling down the wafer from the deposition temperature. After the deposition, the heteroepitaxial layer is in a fully or partially relaxed state depending on the conditions during deposition. When the film forming gases are turned off, the wafer is usually cooled down in a controlled manner. Due to the thermal mismatch of the substrate and the heteroepitaxial layer, new stress is generated and causes a set of secondary relaxation processes. These include the formation of secondary dislocations, roughening of the surface and also bowing of the wafer. Typically a strong increase in the density of TD and the surface roughness towards the wafer edge is observed. The claimed process providing a stress compensating layer allows to minimize the generation of new stress, to eliminate the center to edge non-uniformity in terms of RMS-roughness of the heteroepitaxial layer, to reduce the density of TD and the roughness of the heteroepitaxial layer caused by cross-hatch and to control the bow of the wafer.

Hereinafter, the invention is further explained by referring to figures.

Fig.1 represents a wafer comprising a substrate 1 and a heteroepitaxial layer 2 deposited thereof.

Fig.2 represents a wafer according to the present invention. The wafer comprises a substrate 10 and a heteroepitaxial layer 20 deposited on the front side of the substrate. The wafer further comprises a stress compensating layer 30 deposited on the back side of the substrate. The stress compensating layer preferably comprises a constant composition SiGe layer having an appropriate thickness and composition for compensating the stress which is caused by the heteroepitaxial layer during cooling from the deposition temperature.

Fig.3 represents a preferred wafer according to the present invention. The wafer comprises a substrate 10 and a heteroepitaxial layer deposited on the front side of the substrate, wherein the heteroepitaxial layer comprises a graded SiGe layer 40 deposited on the front side of the substrate and a constant composition SiGe layer 50 deposited on the graded SiGe layer. The wafer further comprises a stress compensating layer deposited on the back side of the substrate, wherein the stress compensating layer comprises a graded SiGe layer 60 deposited on the

back side of the substrate and a constant composition SiGe layer 70 deposited on the graded SiGe layer.

In the preferred embodiment of the invention the stress compensating layer has the same or a similar composition as the heteroepitaxial layer and the same or a similar thickness as the heteroepitaxial layer.

The positive effect of the invention is demonstrated hereinafter by means of examples.

Wafers with a heteroepitaxial layer consisting of a graded SiGe layer and a constant composition SiGe layer on top of the graded SiGe layer were produced in a single wafer CVD reactor by depositing the heteroepitaxial layer on the front side of a silicon substrate wafer. The maximum concentration of germanium in the graded SiGe layer was 70%. The thickness of the graded SiGe layer was 4.6 µm. The concentration of Ge in the constant composition SiGe layer was 70%. The thickness of the constant composition SiGe layer was 1 µm. Before depositing the heteroepitaxial layer on the front side of the substrate, a stress compensating layer has been deposited on the back side of the substrate.

Several experiments were made with a constant composition $Si_{0,3}Ge_{0,7}$ layer as stress compensating layer, wherein the thickness of the layer was varied in order to reveal the stress relieving effect on the heteroepitaxial layer. One experiment (example 4) was made with a stress compensating layer consisting of a graded SiGe layer on the substrate having a maximum concentration of germanium of 70 % and a constant composition SiGe layer on top of the graded SiGe layer.

For the purpose of comparison, two experiments were performed without providing a stress compensating layer before cooling the wafer from the deposition temperature. According to the first comparative example, a graded SiGe layer and a constant composition layer identical to the front side layer of the examples was deposited on a silicon substrate wafer. The maximum concentration of germanium in the graded layer was 70 %. The second comparative example was performed in accordance with the first comparative example, differing only in that 11 strained transitional layers of silicon as taught in US2008/0017952 A1 were provided within the graded SiGe layer for reducing the bow of the resulting wafer. The thickness of each transitional layer was 7 nm.

Further details of the experiments and the results in regard of the reduction of bow, warp, TDD and RMS-roughness are displayed in the following table. The deposition gas for depositing the the stress compensating layer and the heteroepitaxial layer was a mixture of $SiCl_2H_2$ and $GeCl_4$ in hydrogen as a carrier gas.

The density of TD was measured by microscopic inspection after Secco etching. RMS-roughness was measured with an atomic force microscope (40 x 40 µm). Warp analytics was made by using an AFS type device from ADE Corp. USA.

Table:

	comp. example 1	comp. example 2	example 1	example 2	example 3	example 4	example 5
grade rate	20 % / µm	20 % / µm	20 % / µm	20 % / µm	20 % / µm	20 % / µm	20 % / µm
deposition temperature before cooling	1000 °C	1050 °C	1000 °C	1000 °C	1000 °C	1000 °C	1000 °C
thickness of the stress compen-sating layer			2,01 µm	2,51 µm	3,01 µm	5,6 µm	4,82 µm
TDD (center)	$8*10^5$ /cm^2	$5,0*10^6$ /cm^2	$4,8*10^5$ /cm^2	$4,0*10^5$ /cm^2	$4,3*10^5$ /cm^2	$5,4*10^5$ /cm^2	$6,2*10^5$ /cm^2
TDD (edge)	$8,7*10^5$ /cm^2	$> 1*10^7$ /cm^2	$6,1*10^5$ /cm^2	$6,3*10^5$ /cm^2	$6,4*10^5$ /cm^2	$6,3*10^5$ /cm^2	$6,9*10^5$ /cm^2
RMS-roughness (center)	36,4 nm	81,6 nm	30 nm	27 nm	23,1 nm	25,1 nm	27,7 nm
RMS-roughness (edge)	150,4 nm	186,1 nm	37,9 nm	33,5 nm	57,3 nm	43,7 nm	41,5 nm
Bow	-157 µm	-65 µm	-27 µm	2 µm	37 µm	54 µm	121 µm
Warp	290 µm	132 µm	56 µm	32 µm	96 µm	125 µm	274 µm

Claims:

1. A semiconductor wafer comprising
a substrate having a first side and a second side;
a fully or partially relaxed heteroepitaxial layer deposited on the first side of the substrate; and
a stress compensating layer deposited on the second side of the substrate.

2. The wafer as claimed in claim 1, wherein the thickness and the composition of the heteroepitaxial layer is equal or similar to the thickness and the composition of the stress compensating layer.

3. The wafer as claimed in claim 1, wherein the stress compensating layer comprises a graded SiGe layer deposited on the substrate and a constant composition SiGe layer deposited on the graded SiGe layer.

4. The wafer as claimed in claim 1, wherein the stress compensating layer comprises a constant composition SiGe layer deposited on the substrate and having a composition $Si_{(1-x)}Ge_x$.

5. The wafer as claimed in claim 4, wherein the concentration of Ge in the constant composition SiGe layer is from 10 to 80 %.

6. A method for producing a semiconductor wafer comprising
depositing on a first side of a substrate a fully or partially relaxed heteroepitaxial layer at a deposition temperature; and
before cooling the wafer from the deposition temperature, providing a stress compensating layer on a second side of the substrate.

7. The method as claimed in claim 6, providing the stress compensating layer before depositing the fully or partially relaxed heteroepitaxial layer on the first side of the substrate by depositing the stress compensating layer on the second side of the substrate.

8. The method as claimed in claim 6, providing the stress compensating during depositing the fully or partially relaxed heteroepitaxial layer on the first side of the substrate by depositing the stress compensating layer on the second side of the substrate.

9. The method as claimed in claim 6, providing a layer as the stress compensating layer which has the same or a similar thickness and composition as the fully or partially relaxed heteroepitaxial layer.

10. The method as claimed in claim 6, comprising depositing a graded SiGe layer on the second side of the substrate and depositing a constant composition SiGe layer on the graded SiGe layer.

11. The method as claimed in claim 6, comprising depositing a constant composition SiGe layer having a composition $Si_{(1-x)}Ge_x$ on the second side of the substrate.