

**Epitaxially coated semiconductor wafer and method for
producing an epitaxially coated semiconductor wafer**

The invention relates to an epitaxially coated
5 semiconductor wafer comprising a substrate wafer
composed of monocrystalline silicon, a polished
epitaxial layer composed of silicon on the front side
of the substrate wafer, a denuded zone extending from
the polished epitaxial layer into the substrate wafer,
10 and a region adjoining the denuded zone and having BMD
nuclei. The invention also relates to a method for
producing an epitaxially coated semiconductor wafer.

A denuded zone is a near-surface region of the
15 epitaxially coated semiconductor wafer in which oxygen
precipitates called BMDs (bulk micro defects) are not
formed. Said region extends from the upper side surface
into the bulk of the epitaxially coated semiconductor
wafer. The denuded zone is usually provided as a
20 location for accommodating electronic components.

The denuded zone is adjoined by a further region which
extends into the bulk of the semiconductor wafer and in
which BMD nuclei are present. BMD nuclei are developed
25 into BMDs by means of a thermal treatment. BMDs act as
centers of an internal getter which can bind metallic
impurities, in particular. The development of BMD
nuclei into BMDs is also possible in the course of a
thermal treatment which primarily serves for
30 constructing electronic components in the denuded zone.

One trend pursues the aim of providing the highest
possible density of BMDs as near as possible adjoining
the denuded zone. A further trend pursues the aim of
35 restricting the depth of the denuded zone to the amount
necessary for the accommodation of electronic
components.

It is known that momentary rapid heating and cooling of the semiconductor wafer in an atmosphere having a nitriding effect inject vacancies and that the presence of vacancies supports the nucleation of BMD nuclei in the bulk of the semiconductor wafer. A thermal treatment by means of momentary rapid heating and cooling is also called RTA treatment (rapid thermal anneal).

US 2002/0127766 A1 describes a method for producing a semiconductor wafer composed of monocrystalline silicon comprising a polished epitaxial layer, a denuded zone and a region having BMD nuclei. The method comprises an RTA treatment after the deposition of an epitaxial layer.

An RTA treatment, in particular applied to epitaxially coated semiconductor wafers, constitutes a thermal loading associated with the problem of causing slip in the crystal lattice. Furthermore, an RTA treatment also increases the roughness of the surface of the epitaxial layer. Typically, the RMS roughness determined by AFM (atomic force microscope) raises, and a comparatively high number of scattered light centers, called LLS defects (localized light scatterers), are detected, wherein the density of these defects is particularly high in the edge region of the surface of the epitaxial layer.

US2002/0022351 A1 proposes smoothing the surface of the substrate wafer before the deposition of the epitaxial layer in the presence of hydrogen chloride gas and a silane source. However, this method has no influence on processes which impair the roughness of the surface of the epitaxial layer after the deposition thereof.

Therefore, the object of the present invention is to provide an improved method which provides an

epitaxially coated semiconductor wafer composed of silicon having particular properties, concerning the denuded zone and BMD nuclei and the roughness of the surface of the epitaxial layer.

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The object is achieved by means of an epitaxially coated semiconductor wafer, comprising a substrate wafer composed of monocrystalline silicon having a front side and having a rear side;

10 an epitaxial layer composed of silicon having a polished surface on the front side of the substrate wafer, wherein the polished surface has an RMS roughness of not more than 0.055 nm relative to a measurement window having an area of $10\text{ }\mu\text{m} \times 10\text{ }\mu\text{m}$;

15 a denuded zone extending from the polished surface of the epitaxial layer to the rear side of the substrate wafer as far as a depth which, between a center and an edge of the semiconductor wafer, is not less than $6\text{ }\mu\text{m}$ and not more than $14\text{ }\mu\text{m}$, and

20 a region adjoining the denuded zone and having BMD nuclei which can develop into BMDs having a peak density of not less than $3.5 \times 10^9\text{ cm}^{-3}$ at a distance of not more than $70\text{ }\mu\text{m}$ from the polished surface of the epitaxial layer.

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The difference in the RMS roughness, determined by AFM in a measurement window having the area of $10\text{ }\mu\text{m} \times 10\text{ }\mu\text{m}$, between a center zone of the surface and an edge zone of the surface of the epitaxial layer is preferably not more than 5% relative to the roughness in the center zone.

The BMD nuclei are developed into BMDs for example by means of a two-stage precipitation-thermal treatment of the epitaxially coated semiconductor wafer at temperatures of $750\text{ to }850^\circ\text{C}$ for a duration of 1 to 4 h (1st stage) and temperatures of $950\text{ to }1050^\circ\text{C}$ for a duration of 8 to 20 h (2nd stage). However, the

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development of the BMD nuclei into BMDs can also be brought about by means of a comparable thermal treatment of the epitaxially coated semiconductor wafer which is performed principally for the purpose of constructing electronic components.

The substrate wafer preferably has a diameter of at least 300 mm and preferably consists of doped monocrystalline silicon. The dopant is of the n-type, for example phosphorus, or of the p-type, for example boron. The degree of doping is preferably n^- in the case of an n-type doping, and preferably p^+ in the case of a p-type doping, corresponding to a resistivity in the range of 5 to 80 Ωcm in the case of the n-type doping and of 5 to 20 $\text{m}\Omega\text{cm}$, preferably 10 to 20 $\text{m}\Omega\text{cm}$, in the case of the p-type doping.

An epitaxially deposited and polished layer composed of monocrystalline silicon covers the front side of the substrate wafer. The front side is an upper side surface of the substrate wafer; the rear side is a lower side surface of the substrate wafer. The epitaxially deposited layer is preferably likewise doped, particularly preferably in such a way that an n/n^- or a p/p^+ epitaxially coated semiconductor wafer is involved. In the unpolished state, the epitaxially deposited layer preferably has a thickness of not less than 1 μm and not more than 12 μm .

Owing to the below-described method implementation for producing the epitaxially coated semiconductor wafer, the distribution of the BMD nuclei or of the developed BMDs in the thickness direction of the semiconductor wafer is not symmetrical. The denuded zone has a depth of not less than 6 μm and not more than 14 μm . In that case, the density of the BMD nuclei or developed BMDs rises up to a peak density with a high rate of rise and falls less steeply to a level that remains virtually

unchanged as far as the rear side of the substrate wafer. After development of the BMD nuclei into BMDs, the peak density of BMDs on a radius between the center and the edge of the semiconductor wafer is not less than $3.5 \times 10^9 \text{ cm}^{-3}$ and is at a distance from the polished surface of the epitaxial layer of not more than 70 μm . After development of the BMD nuclei into BMDs, the density of BMDs at a distance of 50 μm from the polished surface of the epitaxial layer is preferably not less than 70% of the peak density. The density of developed BMDs at a distance of 200 μm from the polished surface of the epitaxial layer as far as the rear side of the substrate wafer is preferably not greater than 60% of the peak density.

The invention also relates to a method for producing an epitaxially coated semiconductor wafer, comprising providing a substrate wafer composed of monocrystalline silicon having a front side and having a rear side; depositing an epitaxial layer composed of silicon on the front side of the substrate wafer; treating the epitaxial layer with an oxidant; an RTA treatment of the epitaxially coated semiconductor wafer at a temperature in a temperature range of not less than 1160°C and not more than 1185°C for a time period of not less than 15 s and not more than 30 s, wherein the epitaxial layer is exposed to an atmosphere consisting of argon and ammonia and an oxynitride layer forms on the epitaxial layer; removing the oxynitride layer; and polishing the epitaxial layer.

An appropriate source for the substrate wafers required is single crystals composed of silicon, in particular, which were pulled in accordance with the CZ method. In said method, silicon is melted in a crucible composed of quartz and the single crystal grows at the end of a seed crystal which is dipped into the resultant melt

and is raised. The crucible material is partly dissolved by the melt and in this way provides oxygen that is required later for developing BMDs.

5 The substrate wafer is sliced from the single crystal together with a multiplicity of further substrate wafers and subjected to mechanical, chemical and chemical-mechanical processing steps, preferably in order to obtain a substrate wafer whose front side and
10 rear side are as flat as possible and are parallel to one another. Particular preference is given to a substrate wafer having a front side and a rear side, wherein at least the front side is present in a polished state, and having an edge between the front
15 side and the rear side, which is likewise polished.

The substrate wafer contains interstitial oxygen having a concentration of preferably not less than 4.5×10^{17} atoms/cm³ and preferably not more than 7.0×10^{17}
20 atoms/cm³ with the use of the calibration factor in accordance with New ASTM. The elements carbon and nitrogen can be present in the substrate wafer, but preferably not in a concentration that is usually achievable only by intentional addition of such
25 elements. Accordingly, the concentration of carbon is preferably not more than 8.0×10^{15} atoms/cm³ and the concentration of nitrogen is preferably not more than 1.0×10^{12} atoms/cm³. Although the intentional addition of the stated elements would facilitate the formation
30 of BMD nuclei, it should not be carried out, in order to restrict the possibility of the formation of stacking faults (OSF defects) and in order not to impair the electrical properties of the substrate wafer.

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The polished front side of the substrate wafer is epitaxially coated, preferably by means of CVD (chemical vapor deposition) and preferably in a single-

wafer reactor. The coating of the substrate wafer in the single-wafer reactor can be carried out in a known manner, for example as described in US 2010/0213168 A1. A preferred deposition gas contains trichlorosilane as silicon source. The deposition temperature is then preferably not less than 1110°C and not more than 1180°C, particularly preferably 1130°C. Furthermore, the deposition gas preferably contains a dopant of the n-type or p-type. The thickness of the deposited epitaxial layer is preferably not less than 1 µm and not more than 12 µm. The result of this method step is an epitaxially coated semiconductor wafer composed of monocrystalline silicon.

To prepare for the RTA treatment, said semiconductor wafer is preferably cleaned and the epitaxially deposited layer is treated with an oxidant that oxidizes the exposed surface of the epitaxial layer. The thickness of the resultant oxide layer is greater than the thickness of a native oxide. Preferably, an RCA cleaning is carried out, comprising the treatment of the semiconductor wafer firstly with SC-1 cleaning solution containing ammonium hydroxide, hydrogen peroxide and water and then with SC-2 cleaning solution containing hydrogen chloride, hydrogen peroxide and water. The subsequent oxidizing treatment of the epitaxially deposited layer is preferably carried out using ozone as oxidant.

The RTA treatment of the epitaxially coated semiconductor wafer that follows the oxidation comprises rapidly heating said wafer to a temperature in a temperature range of not less than 1160°C and not more than 1185°C, preferably to a temperature of 1170°C, and keeping the epitaxially coated semiconductor wafer at this temperature for a time period of not less than 15 s and not more than 30 s. The epitaxially coated semiconductor wafer is heated

from a starting temperature, which is preferably in the range of 550°C to 650°C, with a rate of rise of temperature that is preferably not less than 20°C/s and not more than 100°C/s. A rate of rise of temperature in the range of 35 to 75°C/s is particularly preferred.

The temperature of the RTA treatment should be as low as possible in order to avoid the occurrence of slip. The RTA treatment is therefore performed in such a way that the epitaxial layer treated with the oxidant is exposed to an atmosphere consisting of a mixture of argon and ammonia. The ratio of argon:ammonia is preferably 10:1 to 24:1, particularly preferably 20:1. In this atmosphere, the intended injection of vacancies can be initiated at a lower temperature than in an atmosphere of nitrogen.

In order to minimize the loading of the epitaxially coated semiconductor wafer by the RTA treatment, it is preferred for the rear side of the epitaxially coated semiconductor wafer and thus the rear side of the substrate wafer, during the RTA treatment, to be exposed to an atmosphere which has no or hardly any nitriding effect at the temperature of the RTA treatment. A suitable atmosphere preferably consists of nitrogen. This measure additionally reduces the risk of slip arising.

At the end of the RTA treatment, the epitaxially coated semiconductor wafer is cooled rapidly, preferably to a temperature of not more than 500°C. For this purpose it suffices to switch off the radiant heating of the RTA apparatus.

On account of the RTA treatment of the epitaxially coated semiconductor wafer in the atmosphere consisting of argon and ammonia, a layer which contains silicon oxynitride and is referred to hereinafter as oxynitride

layer forms from the oxide layer on the epitaxial layer. The oxynitride layer is removed, preferably by etching. An aqueous etchant containing not less than 0.8% and not more than 2.0% hydrogen fluoride is preferably used as the etchant. Removing the oxynitride layer by means of polishing is not provided because the roughness of the front side would be increased and particles would be generated as a result.

The epitaxially deposited layer is polished only after the oxynitride layer has been removed. Chemo mechanical polishing (CMP) with a material removal of not less than 0.05 μm and not more than 0.2 μm is preferred, and may be performed by using, e.g. a polishing tool offered by Applied Materials Inc.. After CMP, the epitaxially coated semiconductor wafer is expediently subjected to final cleaning.

It is furthermore preferred, after the removal of the oxynitride layer and before CMP, firstly to clean the epitaxially coated semiconductor wafer and then to treat it with an oxidant, preferably with ozone. Particular preference is again given to an RCA cleaning comprising the treatment of the semiconductor wafer firstly with SC-1 cleaning solution and then with SC-2 cleaning solution.

The invention is explained in further detail below on the basis of examples and with reference to drawings.

Double-side polished substrate wafers composed of monocrystalline silicon having a diameter of 300 mm were provided. Substrate wafers in accordance with example B1 contained interstitial oxygen in a concentration of 6.1×10^{17} to 6.7×10^{17} atoms/cm³ (New ASTM) and were p-type doped with a resistivity of 18 to 19.5 m Ω cm. Substrate wafers in accordance with example B2 contained interstitial oxygen in a concentration of

5.3 $\times 10^{17}$ to 5.6 $\times 10^{17}$ atoms/cm³ (New ASTM) and were n-type doped with a resistivity of 29 to 30 Ω cm. The substrate wafers were processed to form semiconductor wafers having a polished epitaxial layer using a sequence of method steps in accordance with the invention. The epitaxially deposited layer had a thickness of 4 μ m (example B1) and respectively 9 μ m (example B2). The semiconductor wafers in accordance with example B1 were p/p⁺ epitaxially coated semiconductor wafers, and those in accordance with example B2 were n/n⁻ epitaxially coated semiconductor wafers. The epitaxially deposited layers had a resistivity in the range of 29 to 30 Ω cm.

The temperature of the RTA treatment was 1175°C in the case of all the semiconductor wafers, and the duration of the RTA treatment at this temperature was 15 s and 25 s (example B1) and respectively 15 s, 25 s and 30 s (example B2). All the semiconductor wafers were heated to the temperature of 1175°C with a rate of rise of temperature of 75°C/s, and the epitaxially deposited layer was treated at this temperature in an atmosphere of argon and ammonia in a ratio of 20:1. Thereafter, the semiconductor wafers were cooled with a rate of decrease of temperature of 35°C/s.

After the RTA treatment, the semiconductor wafers were processed further according to the invention to form semiconductor wafers having a polished epitaxial layer and were subsequently subjected to a thermal treatment for the development of BMDs. This thermal treatment was carried out under nitrogen and comprised heating the semiconductor wafers firstly to a temperature of 800°C over a time period of 3 h and subsequently to a temperature of 1000°C over a time period of 16 h. The BMD detection was carried out by means of laser light scattering at a fracture edge using a detection

instrument of the M0441 type from the Raytex Corporation.

Data regarding the determined depths of the denuded
5 zone and the determined densities of BMDs are entered
in table 1 below. The data have the following meaning:
"HZ" means the duration of the RTA treatment at the
temperature of the RTA treatment;
"DZ1 av." means the depth of the denuded zone averaged
10 over the radius of the semiconductor wafer;
"BMD av." means the density of BMDs averaged over the
radius of the semiconductor wafer;
"BMD peak" means the peak density of BMDs determined in
the center of the semiconductor wafer; and
15 "BMD 50 μm " means the density of BMDs found at a depth
of 50 μm in the radial center of the semiconductor
wafer.

Table 1:

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B1									
HZ [s]	15	15	15	25	25	25			
DZ1 av. [μm]	8.4	8.6	7.7	6.3	7.4	7.1			
BMD av. [10^9cm^{-3}]	3.87	3.9	5.36	5.77	5.3	5.94			
BMD peak [10^9cm^{-3}]	6.77	6.77	7.93	8.67	8.65	8.05			
BMD 50 μm [10^9cm^{-3}]	6.08	6.02	8.23	8.02	8.77	8.4			
B2									
HZ [s]	15	15	15	25	25	25	30	30	30
DZ1 av. [μm]	12	13.5	12.1	9.2	9.4	10.7	9.6	9.3	8.8
BMD av. [10^9cm^{-3}]	4.11	3.24	3.20	5.71	4.68	4.92	5.97	5.76	6.33
BMD peak [10^9cm^{-3}]	6.52	5.60	5.62	8.30	7.73	8.48	8.85	8.63	8.97

BMD 50 μm [10^9cm^{-3}]	4.68	3.68	4.03	7.28	6.42	7.02	8.57	7.80	7.68
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The data concerning "DZ av." in table 1 show that the depth of the denuded zone decreases with increasing duration of the RTA treatment, and the data concerning "BMD 50 μm " show that the difference with respect to the peak density at the depth of 50 μm becomes smaller and smaller with increasing duration of the RTA treatment. The depth of the denuded zone corresponds at least to the thickness of the epitaxial layer virtually in all cases.

Fig. 1 to fig. 3 show in a representative manner the depth profile of BMDs for a semiconductor wafer in accordance with example B1 in the radial center ($r=0$ mm), for radius $r=75$ mm and for radius $r=140$ mm.

Table 2

Removal of the oxynitride layer	RMS ($r=0$ mm) [nm]	RMS ($r=75$ mm) [nm]	RMS ($r=140$ mm) [nm]	σ [nm]	σ [%]
no	0.0525	0.057	0.0784	0.01129	18.04
no	0.0518	0.0493	0.0626	0.00577	10.58
yes	0.0507	0.0497	0.0521	0.00098	1.94
yes	0.0483	0.0498	0.0495	0.00064	1.32
yes	0.0492	0.0484	0.0494	0.00043	0.88

Table 2 contains values for the RMS roughness relative to a measurement window having an area of $10\text{ }\mu\text{m} \times 10\text{ }\mu\text{m}$. The data show that the RMS roughness is improved particularly in the edge region of the epitaxially coated semiconductor wafer if the oxynitride layer is removed according to the invention. The standard deviation σ is not more than 5%.

The removal of the oxynitride layer according to the invention is also particularly advantageous with regard to the number of LLS defects which are found on the polished surface after the polishing of the epitaxial layer. Table 3 contains indications concerning the number of scattered light centers having a size of 120 nm or larger which were found before the RTA treatment and after CMP on the surface of the epitaxial layer of two epitaxially coated semiconductor wafers. One of the semiconductor wafers had been produced according to the invention, and the other in almost the same way, but without the removal of the oxynitride layer.

Table 3

Removal of the oxynitride layer	LLS defects before RTA treatment [number]	LLS defects after CMP [number]
no	6	4098
yes	3	3

Patent Claims

1. An epitaxially coated semiconductor wafer, comprising:
a substrate wafer composed of monocrystalline silicon

5 having a front side and having a rear side;

an epitaxial layer composed of silicon having a polished
surface on the front side of the substrate wafer, wherein the
polished surface has an RMS roughness of not more than 0.055 nm
relative to a measurement window having an area of $10\text{ }\mu\text{m} \times 10$

10 μm ;

a denuded zone extending from the polished surface of the
epitaxial layer to the rear side of the substrate wafer as far
as a depth which, between a center and an edge of the
semiconductor wafer, is not less than $6\text{ }\mu\text{m}$ and not more than 14

15 μm ;

a region adjoining the denuded zone and having BMD nuclei
which can develop into BMDs having a peak density of not less
than $3.5 \times 10^9\text{ cm}^{-3}$ at a distance of not more than $70\text{ }\mu\text{m}$ from the
polished surface of the epitaxial layer; and

20 BMD nuclei which can develop into BMDs whose density at a
distance of $200\text{ }\mu\text{m}$ from the polished surface of the epitaxial
layer as far as the rear side of the substrate wafer is not
greater than 60% of the peak density.

25 2. The epitaxially coated semiconductor wafer as claimed in
claim 1, which has BMD nuclei which can develop into BMDs whose
density at a distance of $50\text{ }\mu\text{m}$ from the polished surface of the
epitaxial layer is not less than 70% of the peak density.

30 3. A method for producing an epitaxially coated semiconductor
wafer, comprising

providing a substrate wafer composed of monocrystalline silicon, having a front side and having a rear side;

depositing an epitaxial layer composed of silicon on the front side of the substrate wafer;

5 treating the epitaxial layer with an oxidant;

an RTA treatment of the epitaxially coated semiconductor wafer at a temperature in a temperature range of not less than 1160°C and not more than 1185°C for a time period of not less than 15 s and not more than 30 s, wherein the epitaxial layer is
10 exposed to an atmosphere consisting of argon and ammonia and an oxynitride layer forms on the epitaxial layer;

removing the oxynitride layer; and

polishing the epitaxial layer,

wherein the rear side of the substrate wafer, during the
15 RTA treatment, is exposed to an atmosphere which has no or hardly any nitriding effect at the temperature of the RTA treatment.

4. The method as claimed in claim 3, wherein the oxynitride
20 layer is removed using an aqueous etchant containing not less than 0.8% and not more than 2.0% hydrogen fluoride.