

Method for pulling a single-crystal ingot

Technical Field

Subjects of the present invention are a method for pulling a single-crystal ingot, a method for producing wafers of semiconductor material, and a wafer of
5 monocrystalline silicon.

Prior Art

Monocrystalline wafers (slices) of semiconductor material are the basis of modern-day electronics. They are produced in a multiplicity of process steps, which encompass
10 the pulling of a single-crystal ingot from a melt, the grinding and slicing of the crystal into wafers, and the surface working of the wafers.

Monocrystalline wafers of semiconductor material, especially semiconductor wafers of silicon, are typically produced by first pulling a monocrystalline ingot according to what is called the Czochralski method (CZ). The ingots produced accordingly are divided
15 into crystal pieces by means of saws suitable for that purpose, such as wire saws, internal diameter saws or band saws, and these pieces are typically processed to semiconductor wafers in a wire saw or internal diameter saw. After further mechanical, chemomechanical and/or chemical steps, an epitaxial layer may optionally be deposited on the wafer by means of chemical vapor deposition (CVD).

20 The CZ method typically entails lowering a seed crystal, commonly referred to as the seed, toward a silicon melt having a temperature above 1410°C until contact has been produced with the silicon melt. Crystal growth is accomplished by slowly pulling the seed crystal upward again, with rotation, while the melt solidifies at the developing interface. In this procedure, first a starting cone of the single crystal with increasing
25 diameter, followed by a cylindrical portion with the desired diameter, and lastly a tail cone with decreasing diameter are pulled.

When the seed crystal is brought into contact with the hot silicon melt, stresses occur in the seed crystal and lead to the development of dislocations in the seed crystal. These dislocations may propagate over the entire length of the crystal ingot.

In the majority of cases, these dislocations may be removed from the single crystal by the formation of a thin neck. To form a thin neck, also referred to as a Dash neck, the rotating seed crystal is pulled upward at high velocity so as to reduce the diameter of the substantially cylindrical thin neck to typically 2 to 6 mm. Proceeding from the
5 dislocation-free thin neck, the diameter of the single-crystal ingot is increased again, and a dislocation-free single crystal having the desired diameter can be pulled. This method is also referred to as the Dash technique or Dash necking technique.

Edge dislocations can generally be avoided as a result of the Dash necking technique. For screw dislocations, this is not equally the case. These dislocations cannot always
10 be removed by the Dash necking technique.

EP 1 498 517 A1, for instance, describes how in the case of a seed having the crystal orientation $\langle 110 \rangle$, dislocations in the center of the seed cannot easily be removed by the Dash necking technique. In the case of a seed having a $\langle 110 \rangle$ crystal orientation – that is, if the pulling direction of the crystal runs perpendicularly to the crystal plane
15 with a Miller index of (110) – the immersing of the seed into the melt may be accompanied by formation of slide dislocations in the center, which propagate in axial direction – that is, along the pulling direction of the single-crystal ingot – over the entire length of the ingot. In the case of a crystal orientation of $\langle 100 \rangle$, dislocations also occur in some of the pulled single-crystal ingots even when the Dash necking
20 technique is employed. EP 1 498 517 A1 describes a method for pulling a single-crystal ingot in which the formation of dislocations in the seed is prevented. There are therefore no dislocations requiring removal and the method thus operates without need for the Dash necking technique.

EP 1 498 516 B1 describes a method for producing a single silicon crystal having the
25 crystal orientation $\langle 110 \rangle$, where dislocations in the seed are removed by inclining the seed crystal by a predetermined angle relative to the axial pulling direction, so that the pulling direction is not exactly perpendicular to the crystal plane with a Miller index of (110). The subsequent formation of a thin neck in accordance with the Dash necking technique allows the dislocations to be removed. However, semiconductor wafers
30 having a surface running exactly parallel to the crystal plane $\langle 110 \rangle$ cannot be

produced from a single-crystal ingot produced in accordance with EP 1 498 516 B1, so limiting the suitability of these semiconductor wafers for demanding electrical components involving high switching frequency.

US 4 002 523 A describes a complex method for pulling a single-crystal ingot with a
5 crystal orientation $\langle 110 \rangle$ in which a thin neck with thin and thick regions in alternation is pulled, thereby displacing dislocations running parallel to the growth direction (pulling direction) of the single-crystal gradually away from the axis of the crystal and to the periphery. This increases the probability of the dislocations ending at a surface and so disappearing from the crystal. However, this complex and complicated method
10 requires tapering of the thin neck to 2.5 mm, and so the stability of the thin neck is reduced and it thus becomes more difficult to remove crystals from large crystal ingots.

JP 9 255 490 A2, moreover, proposes using a seed and a melt with equal concentrations of boron, in the context of producing boron-doped single silicon
15 crystals, and thereby preventing the development of dislocations brought about by different lattice constants.

JP 2982053 B2 describes a single-crystal pulling method that likewise operates without need for the Dash necking technique. In this method, the seed is lowered to just above the melt, where it is heated, and then a part of the seed (seed crystal) is
20 immersed into the melt at a rate of 0.05 to 2 mm/min, after which the immersed part of the seed is melted. The immersed part here has a length in vertical direction that corresponds at least to the diameter of the seed. The melting operation also melts the part of the seed crystal which has dislocations caused by thermal stresses. The part of the seed that remains after the melting therefore no longer has any defects.

25 The methods described above are all relatively complicated and inefficient and therefore have only limited usefulness in industrial production. Furthermore, these methods are not sufficiently suitable for producing a single-crystal ingot having the crystal orientation $\langle 110 \rangle$ that is free from near-center defects.

Technical Object of the Invention, and its Achievement

The object on which the present invention is based is that of providing an efficient method for pulling a single-crystal ingot of semiconductor material without near-center defects according to the Czochralski technique. A goal of the present invention in particular is to provide an efficient method which is suitable for providing a dislocation-free single-crystal ingot of semiconductor material having the crystal orientation $\langle 100 \rangle$, $\langle 110 \rangle$ or $\langle 111 \rangle$.

The invention is based on the surprising observation that after the seed has been immersed, it is possible, by the pulling of a seed cone of a defined geometry under defined conditions, to produce a single-crystal ingot having the crystal orientation $\langle 110 \rangle$ that is free from near-center defects, in particular free from near-center screw dislocations.

This object is achieved according to the first aspect of the present invention by the method of the invention for pulling a single-crystal ingot from a silicon melt according to the Czochralski technique. The method comprises the following steps:

- (i) providing a silicon melt and a seed crystal of monocrystalline silicon above the melt, with the silicon melt and/or the seed crystal optionally comprising dopants;
- (ii) lowering the seed crystal until contact is produced between the seed crystal and the silicon melt; and

- (iii) pulling a seed cone, a thin neck, a starting cone and a cylindrical portion of the single-crystal ingot in this order by raising the seed crystal;

wherein the seed cone has an upper diameter of not less than 12 mm and not more than 22 mm, a lower diameter of not less than 2 mm and not more than 10 mm, and an axial length of not less than 75 mm and not more than 300 mm.

Preferred embodiments of the method of the invention according to the first aspect are subjects of dependent claims 2 to 10.

It has surprisingly been determined that with the method of the invention, a single-crystal ingot having the crystal orientation $\langle 110 \rangle$ can be produced that is free from

near-center defects, in particular free from near-center screw dislocations. Moreover, because of the surprisingly high velocities at which the seed crystal can be moved before the start of crystal pulling, as no holding phases are required, the method of the invention is particularly efficient and therefore economically attractive.

5

Near-center defects are linear combinations of various dislocations – for example, of multiple screw dislocations and/or edge dislocations – which are connected by what are called kinks.

Near-center defects come about on contact of the seed (seed crystal) with the melt and they propagate through the thin neck. To be able to propagate through the thin neck, such defects have to continue through the center of the seed crystal across the thin neck to the center of the growing single-crystal ingot. They therefore appear in the topmost part of the cylindrical portion of the single crystal, and hence in the wafers having the desired nominal diameter that are obtained from the topmost part of the cylindrical portion, in the center or at least near-center. Any possible deviation of the pulling direction from the desired crystal orientation results in the dislocations moving away from the center as the length of the growing single crystal increases. With increasing distance from the thin neck, therefore, the dislocations propagating through the single-crystal ingot are able to move further from the center of the growing single-crystal ingot. A near-center dislocation in the sense of the present invention is a dislocation which occurs at a distance of up to 50 mm from the center of the semiconductor wafer, i.e., from the wafer midpoint. A single-crystal ingot is considered dislocation-free in the sense of the present invention if a wafer from the topmost part of the cylindrical portion, more particularly from the topmost 10 cm of the cylindrical portion of the single-crystal ingot, contains no near-center dislocations.

According to the second aspect, the present invention is directed to a method for producing wafers of semiconductor material. This method comprises the following steps:

pulling a single-crystal ingot by the method according to the first aspect;
grinding the single-crystal ingot;
slicing the ground single-crystal ingot into wafers;
grinding and/or lapping the wafers;

polishing the wafers; and
chemically cleaning the wafers.

In one preferred embodiment of the method of the invention according to the second aspect, the method additionally comprises the step of depositing an epitaxial layer of semiconductor material on the wafer of semiconductor material.

According to the third aspect, the present invention relates to a wafer of monocrystalline silicon wherein

the wafer has a nominal diameter of 300 mm and the crystal orientation of the main faces deviates not more than 5° from the orientation $\langle 110 \rangle$,

the wafer optionally comprises dopants, and

the wafer has no dislocations within a radius of 50 mm around the wafer midpoint,

where the wafer is investigated for dislocations according to the following technique:

placing the mirror-etched or polished wafer on a turntable in a dark-field transmission polariscope,

setting the wafer on the turntable into rotation,

irradiating the rotating semiconductor wafer on the turntable with a linear-polarized infrared light beam, while the semiconductor wafer is displaced continuously or discontinuously in radial direction,

determining the site-dependent depolarization and transmission, and

identifying the points at which the light beam is depolarized as dislocations.

Brief Description of the Figures

Fig. 1 shows the measured depolarization distribution of a wafer produced according to the working example, and shows that this wafer was free from near-center defects.

Fig. 2 shows the measured depolarization distribution of a wafer produced according to the comparative example, which exhibited near-center defects.

Detailed Description of the Invention

In the method of the invention according to the first aspect, first in step (i) a silicon melt and a seed crystal of monocrystalline silicon are provided over the silicon melt. The terms “seed crystal” and “seed” are used synonymously. The seed crystal is
5 preferably rotationally symmetrical and is disposed over the silicon melt such that its rotational axis is aligned vertically, i.e., along the pulling direction. The rotational axis is therefore disposed parallel to the pulling direction. More preferably, the seed crystal is cylindrical and its cylinder axis is aligned parallel to the pulling direction.

10 The seed crystal preferably has a diameter of not less than 5 mm and not more than 25 mm. In one particularly preferred embodiment, the seed crystal has a diameter of not less than 14 mm and not more than 22 mm. The axial length of the seed crystal corresponds preferably to at least three times the diameter, more preferably at least four times the diameter, and most preferably at least five times the diameter of the
15 seed crystal. The axial length of the seed crystal which projects downward from the mount of the seed crystal corresponds preferably to at least three times, more preferably at least four times, the diameter of the seed crystal (before the immersing, i.e., before contact has been produced between the seed crystal and the silicon melt). The mount here is an element at the lower end of the pulling shaft or of the cable that
20 serves to secure the upper part of the seed crystal on the pulling shaft or on the cable.

The silicon melt and the seed crystal consist substantially of silicon. In one preferred embodiment, the fraction of silicon in the melt and in the seed crystal is respectively not less than 99.0% by weight, more preferably respectively not less than 99.8% by
25 weight, and most preferably respectively not less than 99.9% by weight. The silicon concentrations in the melt and in the seed crystal may be varied independently of one another.

The silicon melt and/or the seed crystal here may optionally contain dopants, of the p
30 type and/or of the n type, for example. The dopant is for example at least one element selected from boron, aluminum, gallium, indium, carbon, germanium, nitrogen, phosphorus, arsenic, antimony, and oxygen. The seed crystal preferably has a dopant

concentration of less than 10^{15} atoms per cm^3 . The silicon melt preferably has a dopant concentration of less than 10^{15} atoms per cm^3 . The dopant concentration here is the sum of the concentrations of the dopants B, Al, Ga, In, C, Ge, Sn, Pb, N, P, As, Sb, Bi and O.

5

The silicon melt here has a temperature of not less than 1410°C , preferably not less than 1420°C . The melting point of a silicon melt is at around 1410°C . In one embodiment, the melt is superheated. This means that the temperature of the melt is higher than its melting point.

10

In step (ii), the seed crystal is lowered until contact is produced between the seed crystal and the silicon melt. The contact in the sense of the present invention may be at least one selected from a touch, a thermal contact and an electrical contact between the bottom of the seed crystal and the surface of the melt. It is also possible here for part of the seed crystal to be immersed into the silicon melt. The seed crystal is immersed preferably not more than 5 mm, more preferably not more than 2 mm, into the silicon melt. The seed crystal here may be secured on a pulling shaft or a cable by means of which it can be moved downward in vertical direction along the pulling axis and brought into contact with the melt.

20

The lowering and contacting of the seed crystal with the melt in step (ii) takes place with a velocity of not more than 30 mm/min, preferably with a velocity of not less than 5 mm/min and not more than 20 mm/min. Lowering the seed crystal at this velocity makes it possible to reduce the incidence of thermal stresses in the seed crystal as it is being lowered, and so to diminish the development and propagation of dislocations.

25

The seed crystal is aligned along the pulling direction. The rotational axis of the seed crystal, the latter being preferably rotationally symmetrical, therefore runs in vertical direction. Accordingly, the cylinder axis of a particularly preferred cylindrical seed crystal runs in vertical direction. The seed crystal preferably has a $\langle 100 \rangle$ crystal orientation, a $\langle 110 \rangle$ crystal orientation or a $\langle 111 \rangle$ -crystal orientation. In the case of a $\langle 100 \rangle$ crystal orientation, the crystal plane runs with a Miller Index of (100) perpendicularly to the pulling direction, and hence, in the case of a cylindrical seed

30

crystal, perpendicularly to the cylinder axis of the seed crystal. Correspondingly, in the case of a seed crystal having a $\langle 110 \rangle$ crystal orientation, the cylinder axis and the pulling direction run perpendicularly to the crystal plane with a Miller Index of (110). The desired crystal orientation in the sense of the present invention is also present

5 when the angle between the plane running perpendicularly to the pulling direction and the plane having the desired crystal orientation is not more than 5° . This means that an axis disposed perpendicularly to the crystal plane having the desired orientation – for example, a $\langle 100 \rangle$ crystal orientation, a $\langle 110 \rangle$ crystal orientation or a $\langle 111 \rangle$ crystal orientation – can deviate up to 5° from the orientation of the pulling axis, i.e., of the

10 pulling direction. The pulling direction deviates from the desired crystal orientation preferably not more than 4° , more preferably not more than 3° , most preferably not more than 2° . The pulling direction preferably deviates not more than 2° from a $\langle 100 \rangle$ crystal orientation or a $\langle 110 \rangle$ crystal orientation. In this embodiment, therefore, the angle between the pulling direction and the axis perpendicular to the crystal plane with

15 a Miller Index of (100) or (110) is not more than 2° . In a further particularly preferred embodiment, the pulling direction deviates from the desired crystal orientation not more than 1.5° .

After the lowering and contacting of the seed crystal with the silicon melt, in step (iii) of

20 the method of the invention according to the first aspect, a single-crystal ingot can be pulled from the melt by raising of the seed crystal. Here, a seed cone, a thin neck, a starting cone and a cylindrical portion of the single-crystal ingot are pulled in this order. A seed cone in the sense of the present invention is a portion of the growing single crystal which tapers toward the bottom and which preferably has the form of a

25 frustum. The upper diameter here corresponds preferably to the largest diameter, and the lower diameter to the smallest diameter, of the frustoconical portion.

When contact between the seed crystal and the silicon melt is produced, and the immersed part of the seed crystal, where appropriate, is melted, a homogeneous

30 boundary layer is formed between the melt and the solid part of the seed crystal. In step (iii), the pulling shaft or the cable on which the seed crystal is secured can then be pulled slowly upward, with rotation, while the silicon melt solidifies at the developing interface. By variation of pulling velocity, rotational velocity, and

temperature, the growing, rotating crystal ingot attains the particular desired diameter. The diameter of the crystal ingot can be adjusted very precisely by means of suitable regulation.

5 First, in step (iii), a seed cone is pulled; the seed cone has an upper diameter of not less than 12 mm and not more than 22 mm, a lower diameter of not less than 2 and not more than 10 mm, and an axial length of not less than 75 mm and not more than 300 mm. The seed cone therefore tapers downwardly. The seed cone preferably has a length of not less than 150 and not more than 225 mm, an upper diameter of not
10 less than 14 and not more than 20 mm, and a lower diameter of not less than 4 and not more than 6 mm. The upper diameter of the seed cone here corresponds preferably to the diameter of the seed crystal before contact has been produced between the seed crystal and the silicon melt. The angle between a surface line of the seed cone and the rotational axis of the seed cone is preferably not less than 2° and
15 not more than 15°, more preferably not less than 4° and not more than 13°. The pulling of a seed cone having the described geometry allows near-center dislocations, especially screw dislocations, to be removed from the single-crystal ingot. The seed cone preferably has the shape of a frustum. The diameter of the seed cone therefore decreases preferably uniformly with increasing length during the pulling of the crystal
20 ingot, until the lower diameter of the seed cone is reached and a thin neck is pulled. During pulling, the crucible rotates preferably at 5 to 20 revolutions per minute, more preferably 10 to 15 revolutions per minute.

Following the pulling of the seed cone, a thin neck is pulled; the diameter of the thin
25 neck does not exceed the lower diameter of the seed cone. The thin neck preferably has a diameter of not less than 2 and not more than 10 mm, more preferably not less than 4 and not more than 6 mm. In one preferred embodiment, the diameter of the thin neck corresponds to the lower diameter of the seed cone. The thin neck preferably has a length of not less than 100 mm, more preferably not less than 200
30 mm and not more than 600 mm.

Following the pulling of the thin neck, a starting cone is pulled. For this, the diameter of the growing single-crystal ingot is increased continuously until the desired diameter of the single-crystal ingot is reached.

- 5 The desired diameter for the single-crystal ingot is dependent on the desired nominal diameter of the wafers to be produced from the single-crystal ingot. Owing to the reduction in diameter in the fabrication of wafers, as a result of mechanical processing steps such as grinding, the desired diameter for the single-crystal ingot is greater than the nominal diameter. Preferably, the desired diameter for the single-crystal ingot is
10 not less than 1 mm and not more than 20 mm, preferably not less than 2 mm and not more than 10 mm, above the nominal diameter of the wafers of semiconductor material that are to be produced.

The portion with the desired diameter in the single-crystal ingot is also referred to as
15 the cylindrical portion of the single-crystal ingot. In this portion, the diameter is in the range of the desired diameter at each position along the axial direction, i.e., along the pulling direction. The cylindrical portion of the single crystal is therefore the portion in which the diameter, at each position along the axial direction, is greater than the nominal diameter of the wafers of semiconductor material that are to be produced.

- 20 The diameter in the cylindrical portion, at each position along the axial direction, is preferably not less than 1 mm and not more than 20 mm, more preferably not less than 2 mm and not more than 10 mm, above the nominal diameter of the wafers of semiconductor material that are to be produced. The cylindrical portion of the single-crystal ingot is therefore the portion of the single-crystal ingot that is suitable for the
25 production of wafers having the desired nominal diameter.

- The diameter of the cylindrical portion may vary over the axial length of this portion, provided the diameter at each point is at least 1 mm above the desired nominal diameter of the wafers of semiconductor material that are to be produced. In one
30 particularly preferred embodiment, the diameter of the cylindrical portion varies over the axial length of the cylindrical portion by less than 20 mm, preferably by less than 10 mm, with the variation corresponding to the difference between the greatest and the least diameters over the axial length.

The nominal diameter is preferably not less than 150 mm and not more than 300 mm, more preferably not less than 200 mm and not more than 300 mm, most preferably 300 mm. A wafer has the desired nominal diameter when its actual diameter deviates
 5 not more than 5 mm, preferably not more than 3 mm, more preferably not more than 1 mm, from the value set out in the nominal diameter.

After the cylindrical portion of the single-crystal ingot with the desired diameter has been pulled, a tail cone can be pulled and the crystal ingot removed.

10 In step (iii), the pulling velocity is preferably in the range from 0.5 to 10 mm/min, more preferably 2 to 6 mm/min. The rotational velocity of the crystal is preferably in the range from 1 to 20 revolutions per minute, more preferably 5 to 15 revolutions per minute.

15 The temperature of the silicon melt during step (iii) is preferably not less than 1410°C, more preferably not less than 1420°C, and most preferably not less than 1425°C. The temperature at the start of pulling is preferably not more than 1450°C, more preferably not more than 1440°C, most preferably not more than 1435°C. In one particularly
 20 preferred embodiment, the temperature at the start of pulling is not less than 1420°C and not more than 1440°C.

The temperature of the melt may be measured with a measuring unit having an accuracy of 0.1°C. The measurement here is preferably of the temperature at the
 25 surface of the silicon melt. The measuring unit for measuring the temperature at the surface of the silicon melt is preferably a pyrometer. The temperature of the silicon melt at a defined measuring point may be measured with an accuracy of 0.1°C and regulated with an accuracy of 1.0°C. The temperature of the melt may be regulated by way of one or more heating elements, preferably one or more resistance heaters,
 30 which are arranged around the crucible. The heating elements are controlled via a programmable control unit which is connected to the measuring unit and regulates the temperature at the surface of the silicon melt at the measuring point as a function of the measured temperature with an accuracy of 1.0°C.

According to the second aspect of the present invention, wafers of semiconductor material may be produced by performing – subsequent to the method for pulling a single-crystal ingot according to the first aspect – the following steps: grinding the single-crystal ingot; slicing the ground single-crystal ingot into wafers; grinding and/or lapping the wafers; polishing the wafers; and chemically cleaning the wafers. After the end of pulling, therefore, the crystal ingot may in this order be sliced into pieces and ground, sliced into wafers, the wafers subsequently ground or lapped, polished, and chemically cleaned, and so wafers of semiconductor material obtained. An epitaxial layer of semiconductor material may optionally be deposited on the wafers thus obtain. The deposition takes place preferably from the gas phase by means of CVD. The epitaxial layer of semiconductor material consists preferably of – optionally doped – silicon, germanium, silicon carbide or gallium nitride.

The polished wafers may then be investigated for dislocations, utilizing the effect of stress-induced birefringence. This effect is based on the generation of stress fields by dislocations and defects. If a material is exposed to shearing stresses, its refractive index becomes anisotropic and the material becomes birefringent. Incident linear-polarized light is therefore depolarized by the sample in transmission or reflection. Consequently, the depolarization distributions obtained can be interpreted as shear stress distributions.

The polished wafers may be measured for example by means of SIRD (Scanning InfraRed Depolarization). The SIRD measurement is made by means of a dark-field transmission polariscope. In this measurement, a linear-polarized light beam, preferably a laser beam, with fixed positioning irradiates the wafer of semiconductor material under investigation, which for the measurement is placed on a turntable, rotated, and displaced continuously in radial direction. If the crystal structure of the wafer is free from dislocations and stresses, there is no change in the polarization of the light beam. If, however, there are dislocations present, the light beam experiences a local depolarization caused by stress-induced birefringence.

The semiconductor wafers produced by means of the method of the invention may be investigated for near-center defects/dislocations using, for example, an instrument of

type PSI from the manufacturer Semilab or an instrument from the manufacturer PVA Metrology & Plasma Solutions. The lateral resolution of such a measurement is typically in the range from 50 to 100 μm . Determination of the site-dependent depolarization and transmission in a wafer according to the third aspect of the present invention therefore takes place with a lateral resolution of at least 100 μm , preferably 50 μm .

By means of this measurement, a wafer of semiconductor material produced according to the second aspect of the present invention, more particularly a wafer of monocrystalline silicon, having a diameter of 300 mm and a $\langle 110 \rangle$ crystal orientation, may be investigated for dislocations to ascertain whether the wafer is free from near-center defects.

The wafer of monocrystalline silicon according to the third aspect of the present invention has a nominal diameter of 300 mm and the crystal orientation of its main faces deviates not more than 5° from the orientation $\langle 110 \rangle$. The wafer may optionally comprise dopants, with the dopant concentration being preferably less than 10^{15} atoms per cm^3 . The dopant concentration corresponds to the sum of the concentrations of the dopants B, Al, Ga, In, C, Ge, Sn, Pb, N, P, As, Sb, Bi and O.

The wafer according to the third aspect has no dislocations within a radius of 50 mm around the wafer midpoint and is therefore free of near-center defects. The wafer is investigated for dislocations according to the following technique:

- placing the mirror-etched or polished wafer on a turntable in a dark-field transmission polariscope,
- setting the wafer on the turntable into rotation,
- irradiating the rotating semiconductor wafer on the turntable with a linear-polarized infrared light beam, preferably an infrared laser beam, while the semiconductor wafer is displaced continuously or discontinuously in radial direction,
- determining the site-dependent depolarization and transmission, and

identifying the points at which the light beam is depolarized as dislocations. The lateral resolution of the site-dependent depolarization and transmission is preferably in the range from 50 to 100 μm .

- 5 The wafer of monocrystalline silicon according to the third aspect of the present invention may be produced by the method of the invention according to the second aspect. A $\langle 110 \rangle$ crystal orientation in the sense of the third aspect of the present invention is present when the orientation of the main faces of the wafer deviates not more than 5° , preferably not more than 2° , more preferably not more than 1.5° from
10 the $\langle 110 \rangle$ crystal orientation. The orientation of the main face of the front and back sides of the wafer according to the third aspect of the present invention may therefore deviate by up to 5° , preferably not more than 3° , from the orientation of the crystal plane having the Miller Index (110).

Detailed Description of Inventive Working Examples and of Comparative

15 Examples

- In each of the working examples, a cylindrical seed crystal of monocrystalline silicon having a $\langle 110 \rangle$ crystal orientation and a diameter of 19 mm was used for pulling a crystal ingot with $\langle 110 \rangle$ orientation by the Czochralski technique. The seed crystal was fastened on the pulling shaft of a crystal pulling system of type EKZ 3000 from the
20 manufacturer PVA TePla. A quartz crucible filled with solid, high-purity polysilicon from the manufacturer Wacker Chemie was arranged between a resistance heater in the crystal pulling system. After the crystal pulling system had been closed, purged, and evacuated, the quartz crucible with the silicon was heated to provide a silicon melt. The crystal pulling system used additionally comprised a camera system for
25 observing a phase boundary and a pyrometer for determining the temperature of the melt. The precise position and shape of the seed crystal relative to the melt, and also the shape of the growing crystal ingot, particularly the seed cone, could therefore be determined using the camera system.

- The seed crystal was then moved downward at a velocity of 10 mm/min until a part of
30 the seed was immersed into the melt. The seed crystal was then moved slowly upward with rotation and in this way, first of all, a seed cone having a length of 175

mm to 200 mm, an upper diameter of 19 mm and a lower diameter of 5 mm was pulled, by increasing the pulling velocity and rotational velocity correspondingly. Subsequently, a thin neck having a diameter of 5 mm and a length of 300 mm was pulled. This was followed by the pulling of a starting cone and an increase in the
5 diameter to 310 mm.

On attainment of a crystal diameter of more than 310 mm, a cylindrical portion having an approximately constant diameter was pulled by the Czochralski technique. The pulling velocity at this point in time was around 4 mm/min and the rotational velocity of
10 the crystal was 10 revolutions per minute. Lastly, a tail cone with decreasing diameter was pulled.

On conclusion of the pulling of the crystal ingot, the completed crystal ingot was removed and sliced into wafers having a thickness of 900 μm . From these, wafers having a diameter of 200 mm were then produced, and were ground to a thickness of
15 750 μm and mirror-etched.

These wafers were then investigated for stresses. For the investigation of the wafers for stresses, each wafer was placed on a turntable of an instrument of type PSI from the manufacturer Semilab. The instrument had a linear-polarized infrared light source with fixed positioning, and a turntable. During the measurement, the wafer rotating on
20 the turntable was displaced continuously in radial direction, so that the entire surface of the wafer was scanned by the light source. It was possible to show that the wafers had no stresses, more particularly no stresses within a radius of 50 mm around the wafer midpoint. Fig. 1 shows the depolarization distributions ascertained via the measurement for the wafers produced in the working example, and shows that these
25 wafers were free from near-center defects. In the working example, accordingly, wafers of monocrystalline silicon with a $\langle 110 \rangle$ crystal orientation were produced defect-free and without near-center defects.

The comparative example differs from the method of the working examples only in that no seed cone having a geometry in accordance with the method of the invention
30 was pulled. As in the working examples, the crystal ingot produced in the comparative example was also removed and sliced into wafers having a thickness of 900 μm . From these, wafers having a diameter of 200 mm were then produced, which were ground

to a thickness of 750 μm and mirror-etched. These wafers were then investigated for stresses in the same way as the wafers produced in the working examples. Fig. 2 shows the depolarization distribution ascertained for a wafer of monocrystalline silicon produced in the comparative example. In fig. 2, stresses are apparent in the center of the wafers. Accordingly, stresses and hence near-center defects around the wafer midpoint were detected.

What is claimed is:-

1. A method for pulling a single-crystal ingot from a silicon melt according to the Czochralski technique, comprising the following steps:

(i) providing a silicon melt and a seed crystal of monocrystalline silicon above the melt, with the silicon melt and/or the seed crystal optionally comprising dopants;

(ii) lowering the seed crystal until contact is produced between the seed crystal and the silicon melt; and

(iii) pulling a seed cone, a thin neck, a starting cone and a cylindrical portion of the single-crystal ingot in this order by raising the seed crystal;

wherein the seed cone has an upper diameter of not less than 12 mm and not more than 22 mm, a lower diameter of not less than 2 mm and not more than 10 mm, and an axial length of not less than 75 mm and not more than 300 mm,

and wherein the angle between a surface line of the seed cone and the rotational axis of the seed cone is not less than 2° and not more than 15°.

2. The method for pulling a single-crystal ingot as claimed in claim 1, wherein the seed cone has a length of not less than 150 and not more than 225 mm, an upper diameter of not less than 14 and not more than 20 mm, and a lower diameter of not less than 4 and not more than 6 mm.

3. The method for pulling a single-crystal ingot as claimed in claim 1 or 2, wherein the upper diameter of the seed cone corresponds to the diameter of the seed crystal before contact has been produced between the seed crystal and the silicon melt.

4. The method for pulling a single-crystal ingot as claimed in any of claims 1 to 3, wherein the rotational axis of the seed cone runs parallel to the pulling direction.

5. The method for pulling a single-crystal ingot as claimed in any of claims 1 to 4, wherein the seed crystal has a crystal orientation of $\langle 100 \rangle$, a crystal orientation of $\langle 110 \rangle$ or a crystal orientation of $\langle 111 \rangle$.

6. The method for pulling a single-crystal ingot of semiconductor material as claimed in any of claims 1 to 5, wherein the pulling direction deviates not more than 3° from the orientation $\langle 110 \rangle$.
- 5 7. The method for pulling a single-crystal ingot of semiconductor material as claimed in any of claims 1 to 6, wherein the pulling direction deviates not more than 2° from the orientation $\langle 110 \rangle$.
8. The method for pulling a single-crystal ingot as claimed in any of claims 1 to 7,
10 wherein the seed crystal has a dopant concentration of less than 10^{15} atoms per cm^3 .
9. The method for pulling a single-crystal ingot as claimed in claim 8, wherein the dopant concentration is the sum of the concentrations of the dopants B, Al, Ga, In, C, Ge, Sn, Pb, N, P, As, Sb, Bi and O.
- 15 10. A method for producing wafers of semiconductor material, comprising the following steps:
pulling a single-crystal ingot by the method as claimed in any of claims 1 to 9,
grinding the single-crystal ingot;
20 slicing the ground single-crystal ingot into wafers;
grinding and/or lapping the wafers;
polishing the wafers; and
chemically cleaning the wafers.
- 25 11. The method for producing wafers of semiconductor material as claimed in claim 10, wherein the method additionally comprises the following step:
depositing an epitaxial layer of semiconductor material on the wafer of semiconductor material.
- 30 12. A wafer of monocrystalline silicon, wherein the wafer has a nominal diameter of 300 mm and the crystal orientation of the main faces deviates not more than 5° from the orientation $\langle 110 \rangle$,
the wafer optionally comprises dopants, and

the wafer has no dislocations within a radius of 50 mm around the wafer midpoint,

where the wafer is investigated for dislocations according to the following technique:

- 5 placing the mirror-etched or polished wafer on a turntable in a dark-field transmission polariscope,
- setting the wafer on the turntable into rotation,
- irradiating the rotating semiconductor wafer on the turntable with a linear-polarized infrared light beam, while the semiconductor wafer is displaced
- 10 continuously or discontinuously in radial direction,
- determining the site-dependent depolarization and transmission, and
- identifying the points at which the light beam is depolarized as dislocations.