SEMICONDUCTOR DEVICE AND PRODUCTION METHOD THEREOF

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of Japanese Patent Application No. 2009-189262 filed on August 18, 2009, the entire disclosure of which is incorporated by reference herein.

[0002] This application relates generally to a semiconductor device and production method thereof.

BACKGROUND

[0003] Semiconductor integrated circuits, particularly integrated circuits using MOS transistors, have increasingly been highly integrated. MOS transistors in integrated circuits have been downsized to nano sizes as the integration level is increased. As MOS transistors become smaller, problems occur such as difficulty in controlling the leak current and difficulty in reducing the area occupied by the circuits while assuring a necessary current quantity. In order to resolve these problems, surrounding gate transistors (SGT) have been proposed in which the source, gate, and drain are provided on a substrate in the vertical direction and the gate surrounds a columnar semiconductor layer (for example, see Patent Literature 1)

[0004] [Patent Literature 1] Unexamined Japanese Patent Application KOKAI Publication No. H2-71556

[0005] In an SGT, a channel region is formed in the side surface of a columnar semiconductor layer to surround the columnar semiconductor layer. Therefore, it is possible to attain a large width of the gate in a small occupied area. In order for an SGT having this structure to operate, it is necessary for a large ON current to flow in a small occupied area. However, because it is difficult to apply a voltage on the source and drain in accordance with the desired current when the source and drain have high resistance, the desired current cannot flow. Therefore, a method of producing an SGT in which the source and drain are designed to have low resistance is necessary. Furthermore, it is also necessary to reduce the resistance of contacts in order for a large ON current to flow in the small occupied area.

[0006] In the SGT, the columnar semiconductor layer needs to have a small diameter in

order to diminish leak current accompanying downsizing.

[0007] When the columnar semiconductor layer has a small diameter, the diameter of the columnar semiconductor layer is smaller than that of the contact layer formed on the columnar semiconductor layer. In this case, if over-etching occurs during forming contact holes by etching in the step of forming a contact layer on the columnar semiconductor layer, short circuits between the contact layer on the columnar semiconductor layer and the gate electrode formed around the columnar semiconductor layer may easily occur

SUMMARY

[0008] The purpose of the present application is to provide a structure of a contact layer preventing short circuits between the contact layer on a columnar semiconductor layer and the gate electrode formed around the columnar semiconductor layer and obtaining low and stable contact resistance, and a production method thereof.

[0009] In order to achieve the above purpose, a method for producing a semiconductor device according to a first aspect of the present application comprises:

a step of preparing a structure provided with a substrate, a planar semiconductor layer formed above the substrate and a columnar semiconductor layer formed on the planar semiconductor layer;

a step of forming a first source or drain region in a lower part of the columnar semiconductor layer and in the planar semiconductor layer;

a step of forming a gate insulating film around the columnar semiconductor layer;

a step of forming a gate electrode on the gate insulating film so as to surround the columnar semiconductor layer;

a second drain or source region formation step of forming a second drain or source region in an upper part of the columnar semiconductor layer;

a contact stopper film formation step of forming a contact stopper film on a resultant structure of the second drain or source region formation step;

a step of forming a contact interlayer film on the contact stopper film so as to embed a resultant structure of the contact stopper film formation step; and

a contact layer formation step of forming a first contact layer on the second drain or source region, wherein

the contact layer formation step comprises: a pattern formation step of forming a first pattern on the contact interlayer film, the first pattern corresponding to a region where the first contact layer is to be formed; a contact hole formation step of etching the contact interlayer film to the contact stopper film using the first pattern so as to form a first contact hole for the first contact layer; and a contact stopper film removal step of removing the contact stopper film remaining at a bottom of the first contact hole by etching, and

a projection of a bottom surface of the first contact hole onto the substrate is within a circumference of a projected profile of the contact stopper film onto the substrate, the contact stopper film formed on a top surface and an upper sidewall of the columnar semiconductor layer.

[0010] The contact layer formation step further may comprise a second contact layer formation step of forming a second contact layer on the first source or drain region;

the second contact layer formation step comprises: a step of forming a second pattern on the contact interlayer film, the second pattern corresponding to a region where the second contact layer is to be formed; a step of etching the contact interlayer film to the contact stopper film using the second pattern to form a second contact hole for the second contact layer; and a step removing the contact stopper film remaining at a bottom of the second contact hole by etching,

the second contact hole is formed so that a side surface of the second contact hole is nearly perpendicular to the substrate, and

the first contact hole is formed so that an average inclination of a side surface of the first contact hole is larger than an average inclination of a side surface of the second contact hole.

[0011] The contact layer formation step may further comprise a second contact layer formation step of forming a second contact layer on the first source or drain region and a third contact layer formation step of forming a third contact layer on a gate wire extending from the gate electrode,

the second contact layer formation step comprises: a step of forming a second pattern on the contact interlayer film, the second pattern corresponding to a region where the second contact layer is to be formed; a step of etching the contact interlayer film to the contact stopper film using the second pattern to form a second contact hole for the second contact layer; and a step of removing the contact stopper film remaining at a bottom of the second contact hole by etching,

the third contact layer formation step comprises: a step of forming a third pattern on the contact interlayer film, the third pattern corresponding to a region where the third contact layer is to be formed; a step of etching the contact interlayer film to the contact stopper film using the third pattern to form a third contact hole for the third contact layer; and a step of removing the contact stopper film remaining at a bottom of the third contact hole by etching,

the second contact hole is formed so that a side surface of the second contact hole is nearly perpendicular to the substrate,

the third contact hole is formed so that a side surface of the third contact hole is nearly perpendicular to the substrate, and

the first contact hole is formed so that an average inclination of a side surface of the first contact hole is larger than an average inclination of a side surface of the second contact hole.

[0012] The contact layer formation step may further comprise: a second contact layer formation step of forming a second contact layer on the first source or drain region; and a third contact layer formation step of forming a third contact layer on a gate wire extending from the gate electrode,

the second contact layer formation step comprises: a step of forming a second pattern on the contact interlayer film, the second pattern corresponding to a region where the second contact layer is to be formed; a step of etching the contact interlayer film to the contact stopper film using the second pattern to form a second contact hole for the second contact layer; and a step of removing the contact stopper film remaining at a bottom of the second contact hole by etching,

the third contact layer formation step comprises: a step of forming a third pattern on the contact interlayer film, the third pattern corresponding to a region where the third contact layer is

to be formed; a step of etching the contact interlayer film to the contact stopper film using the third pattern to form a third contact hole for the third contact layer; and a step of removing the contact stopper film remaining at a bottom of the third contact hole by etching,

the second contact hole is formed so that a side surface of the second contact hole is nearly perpendicular to the substrate,

the first contact hole is formed so that an average inclination of a side surface of the first contact hole is larger than an average inclination of a side surface of the second contact hole, and

the third contact hole is formed so that an average inclination of a side surface of the third contact hole is larger than an average inclination of a side surface of the second contact hole.

[0013] The contact layer formation step may further comprise a second contact layer formation step of forming a second contact layer on the first source or drain region,

the second contact layer formation step comprises: a step of applying a second resist on the contact interlayer film and patterning the second resist using lithography to form a second pattern, the second pattern corresponding to a region where the second contact layer is to be formed; and a step of etching the contact interlayer film to the contact stopper film using the second pattern to form a second contact hole for the second contact layer,

in the contact layer formation step, a third contact layer is further formed on a gate wire extending from the gate electrode,

in the pattern formation step, the first patter is formed so as to correspond to the region where the first contact layer is to be formed and the region where the third contact layer is to be formed by applying a first resist on the contact interlayer film and patterning the first resist using lithography,

in the contact hole formation step, the first contact hole and a third contact hole for the third contact layer are formed by etching the contact interlayer film to the contact stopper film using the first pattern,

the contact stopper film removal step is performed after the first contact hole, the second contact hole and the third contact hole have been formed,

in the contact stopper film removal step, the contact stopper film remaining at bottoms of the first contact hole, the second contact hole and the third contact hole are removed by etching,

the second contact hole is formed so that a side surface of the second contact hole is nearly perpendicular to the substrate,

the first contact hole is formed so that an average inclination of a side surface of the first contact hole is larger than an average inclination of a side surface of the second contact hole, and

the third contact hole is formed so that an average inclination of a side surface of the third contact hole is larger than an average inclination of a side surface of the second contact hole.

[0014] The contact layer formation step may further comprise a second and third contact layers formation step of forming a second contact layer on the first source or drain region and forming a third contact layer on a gate wire extending from the gate electrode,

the second and third contact layers formation step comprises: a step of applying a second resist on the contact interlayer film and patterning the second resist using lithography to form a second pattern, the second pattern corresponding to a region where the second contact layer is to be formed and a region where the third contact layer is to be formed; and a step of etching the contact interlayer film to the contact stopper film using the second pattern to form a second contact hole for the second contact layer and a third contact hole for the third contact layer,

in the pattern formation step, the first patter is formed so as to correspond to the region where the first contact layer is to be formed by applying a first resist on the contact interlayer film and patterning the first resist using lithography,

the contact stopper film removal step is performed after the first contact hole, the second contact hole and the third contact hole have been formed,

in the contact stopper film removal step, the contact stopper film remaining at bottoms of the first contact hole, the second contact hole and the third contact hole are removed by etching,

the second contact hole is formed so that a side surface of the second contact hole is nearly perpendicular to the substrate,

the third contact hole is formed so that a side surface of the third contact hole is nearly perpendicular to the substrate,

the first contact hole is formed so that an average inclination of a side surface of the first contact hole is larger than an average inclination of a side surface of the second contact hole, and

the first contact hole is formed so that the average inclination of the side surface of the first contact hole is larger than an average inclination of a side surface of the third contact hole.

[0015] The method may further comprise an oxide film formation step of forming an oxide film in a form of a sidewall on an upper sidewall of the columnar semiconductor layer, wherein

in the contact stopper film formation step, the contact stopper film is formed on a resultant structure of the oxide film formation step, and

the contact stopper film is a silicon nitride film.

[0016] The semiconductor device according to a second aspect of the present application comprises:

a substrate;

a planar semiconductor layer formed on the substrate;

a columnar semiconductor layer formed on the planar semiconductor layer;

a first source or drain region formed at a bottom of the columnar semiconductor layer;

a second drain or source region formed in an upper part of the columnar semiconductor layer;

a gate insulating film formed around the columnar semiconductor layer;

a gate electrode formed on the gate insulating film so as to surround the columnar semiconductor layer;

a first contact layer formed on the second drain or source region;

a second contact layer formed on the first source or drain region; and

a third contact layer formed on a gate wire extending from the gate electrode,

wherein a side surface of the second contact layer is nearly perpendicular to the substrate, and

an average inclination of a side surface of the first contact layer is larger than an average inclination of the side surface of the second contact layer.

[0017] The average inclination of the side surface of the third contact layer may be larger than the average inclination of the side surface of the second contact layer.

[0018] The side surface of the third contact layer may be nearly perpendicular to the substrate, and

the average inclination of the side surface of the first contact layer may be larger than the average inclination of the side surface of the third contact layer.

[0019] The semiconductor device according to a third aspect of the present application comprises:

a substrate;

a columnar semiconductor layer formed above the substrate;

a first source or drain region formed at a bottom of the columnar semiconductor layer;

a second drain or source region formed in an upper part of the columnar semiconductor layer;

a gate insulating film formed around the columnar semiconductor layer;

a gate electrode formed on the gate insulating film so as to surround the columnar semiconductor layer;

a first contact layer formed on the second drain or source region;

a second contact layer formed on the first source or drain region;

a third contact layer formed on a gate wire extending from the gate electrode; and

a first insulating film sidewall formed on an upper sidewall of the columnar semiconductor layer;

wherein a projection of a bottom surface of the first contact layer onto the substrate is within a circumference of a projected profile of the first insulating film sidewall onto the substrate.

[0020] The semiconductor device may further comprise a contact stopper film formed on the

first insulating film sidewall, wherein:

the first insulating film sidewall is a silicon oxide film, and

the contact stopper film is a silicon nitride film.

[0021] Here, the expression "above" the substrate means on the substrate or above the substrate via some layers formed on the substrate.

[0022] According to the present invention , it is possible in a vertical transistor to prevent short circuits between a contact layer on a columnar semiconductor layer and a gate electrode formed around the columnar semiconductor layer. Furthermore, according to the present invention, it is possible to obtain low and stable contact resistance.

BRIEF DESCRIPTION OF THE DRAWINGS

[0023] A more complete understanding of this application can be obtained when the following detailed description is considered in conjunction with the following drawings, in which:

FIG. 1 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 2 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 3 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 4 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 5 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 6 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 7 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 8 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 9 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 10 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 11 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 12 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 13 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 14 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 15 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 16 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 17 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 18 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 19 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 20 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 21 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 22 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 23 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 24 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 25 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 26 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 27 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 28 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 29 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 30 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 31 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 32 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 33 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 34 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 35 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 36 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 37 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 38 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 39 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 40 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 41 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 42 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 43 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, with (a) showing a planar view and (b) showing a cross-sectional view at the line A-A' in (a);

FIG. 44 is a drawing explaining an exemplary production process of the semiconductor device according to a first embodiment, and shows a cross-sectional view at the line B-B' in the planar view of FIG. 43;

FIG. 45A is a cross-sectional view showing the upper part of the columnar silicon layer in a semiconductor device according to a comparison example;

FIG. 45B is a cross-sectional view showing the upper part of the columnar silicon layer in a semiconductor device according to a comparison example;

FIG. 46A is a plane view around the columnar silicon layer of a semiconductor device according to a first embodiment;

FIG. 46B is a cross-sectional view of the upper part of the columnar silicon layer of a semiconductor device according to a first embodiment;

FIG. 46C is a cross-sectional view of the upper part of the columnar silicon layer of a variation of the semiconductor device according to a first embodiment;

FIG. 47A is a plane view around the columnar silicon layer of a variation of the semiconductor device according to a first embodiment;

FIG. 47B is a cross-sectional view showing the shape of the upper part of the columnar silicon layer of a variation of the semiconductor device according to a first embodiment;

FIG. 48A is a cross-sectional view showing the shape of the upper part of the columnar silicon layer of a semiconductor device according to another embodiment of the present invention;

FIG. 48B is a cross-sectional view showing the shape of the upper part of the columnar silicon layer of a semiconductor device according to another embodiment; and

FIG. 48C is a cross-sectional view showing the shape of the upper part of the columnar silicon layer of a semiconductor device according to another embodiment.

DETAILED DESCRIPTION

[0024] FIG. 43is a drawing showing an NMOS SGT of a semiconductor device according to a first embodiment of, with part (a) showing a planar view and part (b) showing a cross-sectional view along the cut line A-A' in part (a). FIG. 44 is a cross-sectional view along the cut line B-B' in the planar view (a). An NMOS SGT of a semiconductor device according to the first embodiment is described hereafter with reference to FIGS. 43 and 44.

[0025] A planar silicon layer **112** that is the planar semiconductor layer is formed on a silicon substrate **110** that is the substrate. A columnar silicon layer **113** that is the columnar semiconductor layer is formed on the planar silicon layer **112**. A source diffusion layer **200** is formed in the lower part of the columnar silicon layer **113** and in the planar silicon layer **112**. A drain diffusion layer **201** is formed in the upper part of the columnar silicon layer **113**. A body **309** is formed between the source diffusion layer **200** and the drain diffusion layer **201**. A gate insulating film **124** is formed around the columnar silicon layer **113**. Furthermore, a gate electrode **141a** is formed on the gate insulating film **124** so as to surround the columnar silicon layer **113**. A gate wire **141b** extends from the gate electrode **141a**. The gate electrode **141a** comprises a part of an amorphous silicon film **141** surrounding the columnar silicon layer **113** and a part of a metal-silicon compound layer **151**. In addition, the gate wire **141b** comprises another part of the amorphous silicon film **141** and another part of the metal-silicon compound layer **151**.

[0026] A first insulating film **303** is formed between the gate electrode **141a** and the source diffusion layer **200**. The first insulating film **303** is an oxide film thicker than the gate insulating film **124**. By forming the first insulating film **303**, which is an oxide film thicker than the gate insulating film **124**, between the gate electrode **141a** and gate wire **141b** extending from the gate electrode **141a** and the source diffusion layer **200**, parasitic capacitance between the gate electrode **141a** and gate wire **141b** and the source diffusion layer **200** can be reduced.

[0027] A first insulating film sidewall (an oxide film) **134** is formed. The first insulating film sidewall **134** is an insulating film in the form of a sidewall on the upper sidewall of the columnar silicon layer **113** and on the upper surface of the gate electrode **141a**. Furthermore, a second insulating film sidewall **133** is formed. The second insulating film sidewall **133** is an insulating film in the form of a sidewall on the sidewalls of the gate electrode **141a** and gate wire **141b**. When the first insulating film sidewall **134** is composed of an oxide film, the condition for etching a contact stopper film **135** is preferably set to yield a high selectivity ratio between the contact stopper film **135** composed of a nitride film and the first insulating film sidewall **134** composed of an oxide film in the below-described process of forming a contact hole for a first contact layer **173** on the upper part of the columnar silicon layer **113**. Accordingly, over-etching of the first insulating film sidewall **134** during the formation of the contact hole can be prevented.

[0028] A metal-silicon compound layer **153** is formed in the top part of the source diffusion layer **200**. A metal-silicon compound layer **152** is formed in the top part of the drain diffusion layer **201**.

[0029] A second contact layer **174** is formed on the metal-silicon compound layer **153** provided in the top part of the source diffusion layer **200**. A first contact layer **173** is formed on the metal-silicon compound layer **152** provided in top part of the drain diffusion layer **201**. A third contact layer **172** is formed on the top surface of the gate wire **141b** extending from the gate electrode **141a**. The shape of the first contact layer **173** formed on the columnar silicon layer **113** will be described later.

[0030] The source diffusion layer **200** is connected to a ground potential (GND potential)

and the drain diffusion layer **201** is connected to a Vcc potential. By applying a potential in the range of between 0 and Vcc to the gate electrode **141a**, the SGT of this embodiment operate as a transistor.

[0031] Here, the diffusion layer formed in the upper part of the columnar silicon layer**113** may serve as a source diffusion layer and the diffusion layer formed in the lower part of the columnar silicon layer **113** may serve as a drain diffusion layer.

[0032] An exemplary method for producing the SGT which is a semiconductor device according to the first embodiment of the present application is described hereafter with reference to FIGS. 1 to 43. In the figures, the same components are referred to by the same reference numbers. FIGS. 1 to 43 show an exemplary method for producing the SGT according to the present invention. In each figure, part (a) is a plane view and part (b) is a cross-sectional view along a cut line A-A'.

[0033] Referring to FIG. 1, a pad oxide film **121** is formed on a silicon substrate **110**.

[0034] Referring to FIG. 2, a first nitride film **130** is formed on the pad oxide film **121** and a first amorphous silicon film **140** is formed on the first nitride film **130**. The first amorphous silicon film may also be a film composed of polysilicon, for example.

[0035] Referring to FIG. 3, a resist is applied to the first amorphous silicon film **140** and patterned using lithography techniques to form a resist pattern **301** corresponding to the area where the columnar silicon layer **113** is to be formed in a later step.

[0036] Referring to FIG. 4, the first amorphous silicon film **140** and the first nitride film **130** are etched with the first resist pattern **301** to form a first hard mask. Then, the pad oxide film **121** is etched using the first hard mask.

[0037] Referring to FIG. 5, the first resist pattern **301** is removed.

[0038] Referring to FIG. 6, a columnar silicon layer **113** is formed by dry-etching the silicon substrate **110** using the first hard mask as a mask. The first hard mask is composed of the first nitride film **130** and the first amorphous silicon film **140**. During the dry-etching step, the first amorphous silicon film **140** is also etched. After the first amorphous silicon film **140** is

completely etched, the plasma emission intensity detectable in a dry-etching device is changed. Therefore, the etching end point can be detected by detecting the change in the plasma emission intensity. Accordingly, the height of the columnar silicon layer **113** can be controlled in a stable manner not dependent on the etching rate.

[0039] In order to apply the above end point detection method to this process, the thickness of the amorphous silicon film **140** prior to the formation of the columnar silicon layer **113** through dry-etching must be smaller than the height of the columnar silicon layer **113**.

[0040] Referring to FIG. 7, the surfaces of the columnar silicon layer **113** and silicon substrate **110** are sacrificially oxidized to form a sacrificial oxide film **123** for smoothing the side surface of the columnar silicon layer **113** that will form a channel and removing the silicon surface in which carbon and like is implanted during the dry-etching step.

[0041] Referring to FIG. 8, a resist is applied to the resultant structure of the above step, and patterned by lithography techniques to form a resist pattern **150** corresponding to the area where a planar silicon layer **112** is to be formed. Here, the sacrificial oxide film **123** formed in the surface of the columnar silicon layer **113** and silicon substrate **110** protects the silicon surface from contaminants such as byproducts of the subsequent dry-etching step.

[0042] Referring to FIG. 9, the silicon substrate **110** is dry-etched with the resist pattern **150** to form a planar silicon layer **112**.

[0043] Referring to FIG. 10, the resist pattern **150** is removed.

[0044] Referring to FIG. 11, a filler oxide film **120** is deposited so as to cover the resultant structure of the above steps, and planarized.

[0045] Referring to FIG. 12, the planarized filler oxide film **120** is etched to expose the surface of the planar silicon layer **112.**

[0046] Referring to FIG. 13, an offset spacer **307** is formed on the side surface of the columnar silicon layer **113**. The offset spacer **307** is composed of electrically conductive material such as silicon oxide. The offset spacer **307** prevents dopants from being implanted into the columnar

silicon layer **113** through the sidewall of the columnar silicon layer **113** during the implantation of dopants in the next step.

[0047] Referring to FIG. 14, a dopant such as arsenic or phosphorus is implanted in the planar silicon layer **112** to form a source diffusion layer **200** in the lower part of the columnar silicon layer **113** and in the planar silicon layer **112**.

[0048] In the above step, the first nitride film **130** formed on the columnar silicon layer **113** prevents dopants from being implanted into the upper part of the columnar silicon layer **113**. As described above, the implantation of dopants into the source diffusion layer **200** formed in the planar silicon layer **112** and the implantation of dopants into the drain diffusion layer **201** formed in the upper part of the columnar silicon layer **113** are separately performed. This allows the conditions of the implantation to be easily optimized separately. Therefore, it is possible to prevent short channel effect and leak current effectively.

[0049] Referring to FIG. 15, the offset spacer **307** is etched to be removed.

[0050] Referring to FIG. 16, an insulating film **303a** such as an oxide film is formed. The insulating film **303a** is formed thickly on the lower part of the columnar silicon layer **113**, on the source diffusion layer **200**, and on the top of the columnar silicon layer **113** and the insulating film **303a** is formed thinly on the sidewall of the columnar silicon layer **113**.

[0051] Referring to FIG. 17, the insulating film **303a** on the sidewall of the columnar silicon layer **113** is etched. Preferably, the etching is performed isotropically. As described above, the insulating film **303a** is formed thickly at the bottom of the columnar silicon layer **113**, above the source diffusion layer **200** and above the top of the columnar silicon layer **113** and is formed thinly around the sidewall of the columnar silicon layer **113**. Consequently, even after etching the insulating film **303a** around the sidewall of the columnar silicon layer **113**, part of the insulating film **303a** remains at the bottom of the columnar silicon layer**113**, above the source diffusion layer **200** and above the top of the columnar silicon layer **113** so as to form an insulating film **303b** at the bottom of the columnar silicon layer **113** and above the source diffusion layer **200** and form an insulating film **306** above the top of the columnar silicon layer

113. The insulating film **303b** is arranged between the gate electrode **141a** and gate wire **141b**, which are to be formed later, and the source diffusion layer **200** and becomes a first insulating film **303** thicker than the gate insulating film **124**. The first insulating film **303** serves to reduce parasitic capacitance between the gate electrode **141a** and gate wire **141b** and the source diffusion layer **200**.

[0052] The first insulating film **303** that is formed so as to be arranged between the gate electrode **141a** and gate wire **141b** and the planar silicon layer **112** in a later step may also be formed by forming an insulating film to embed the columnar silicon layer **113**, flattening and etching back it.

[0053] Referring to FIG. 18, a gate insulating film **124** such as an oxide film and silicon oxynitride film is formed on the side surface of the columnar silicon layer **113**.

Referring to FIG. 19, a second amorphous silicon film **141** that is a gate conductive film is formed to embed the columnar silicon layer **113**. The second amorphous silicon film **141** may also be a film composed of polysilicon.

[0054] Referring to FIG. 20, the second amorphous silicon film **141** is polished by chemical mechanical polishing (CMP) method to flatten the top surface thereof. Using the nitride film **130** that is the first hard mask as the stopper in the CMP, the amount of amorphous silicon polished by CMP can be controlled in a well reproducible manner.

[0055] Referring to FIG. 21, the second amorphous silicon film **141** that is the gate conductive film is etched back to determine the gate length.

[0056] Referring to FIG. 22, a first oxide film **125** is formed on the resultant structure of the above steps and a second nitride film **131a** is formed on the first oxide film **125**. The first oxide film **125** protects the top surface of the gate electrode **141a** from wet or dry treatments performed in later steps, therefore it possible to prevent fluctuation in the gate length, variation in the gate length and damage to the gate insulating film **124** from the top surface of the gate electrode **141a**.

[0057] Referring to FIG. 23, the second nitride film **131a** is etched back to form a third

insulating film sidewall **131**. Here, the first oxide film **125** is also etched. The thickness of the third insulating film sidewall **131** corresponds to the thickness of the gate electrode **141a** Therefore, it possible to form a gate electrode having a desired thickness by adjusting the thickness of the second nitride film **131a** and etch-back conditions thereof.

[0058] Referring to FIG. 24, a dopant such as phosphorus (P) is implanted in the second amorphous silicon film (gate conductive film) **141**, and then the implanted dopant is activated.

[0059] Referring to FIG. 25, an antireflection coating (BARC) layer **161** is formed on the resultant structure of the above steps and a resist is applied, and a resist pattern **160** corresponding to the pattern of the gate wiring which is to be formed in a later step is formed by patterning this resist using lithography techniques.

[0060] Referring to FIG. 26, the BARC layer **161** and the second amorphous silicon film **141** are etched using the resist pattern **160** as a mask to form the gate electrode **141a** and the gate wire **141b**.

[0061] Referring to FIG. 27, part of the insulating film **303b** is removed by dry or wet etching to expose the surface of the source diffusion layer **200** and form the first insulating film **303**.

[0062] Referring to FIG. 28, the resist pattern **160** and the BARC layer **161** are removed. Next, a fourth oxide film **305** is formed on the exposed surface of the gate electrode **141a** and gate wire **141b**. The fourth oxide film **305** can protect the gate electrode during a later step of removing the first nitride film **130** and the third insulating film sidewall **131**.

[0063] Referring to FIG. 29, the first nitride film **130** and the third insulating film sidewall **131** on the columnar silicon layer **113** are removed by dry or wet etching.

[0064] Referring to FIG. 30, the pad oxide film **121**, the first oxide film **125**, and the fourth oxide film **305** are removed by dry or wet etching to expose the source diffusion layer **200**.

[0065] Referring to FIG. 31, a third insulating film **132** is formed on the resultant structure of the above steps.

[0066] Referring to FIG. 32, the third insulating film **132** is etched back to expose the top surface of the source diffusion layer **200** and the top surface of the columnar silicon layer **113**. In this step, the third insulating film **132** remains in sidewall shape on the sidewall of the columnar silicon layer **113** and the sidewalls of the gate electrode **141a** and gate wire **141b** to form a first insulating film sidewall **134** and a second insulating film sidewall **133**. The first insulating film sidewall **134** separates the gate electrode **141a** and gate wire **141b** from the drain diffusion layer **201** which is to be formed later in the upper part of the first columnar silicon layer **113**. And, the second insulating film sidewall **133** separates the gate electrode **141a** and gate wire **141b** from the source diffusion layer **200**. Therefore, short circuit between the gate electrode **141a** and gate wire **141b** and the source diffusion layer **200** due to metal-semiconductor compounds formed in subsequent steps can be prevented. And, short circuit between the gate electrode **141a** and gate wire **141b** and the drain diffusion layer **201** due to metal-silicon compounds formed in subsequent steps can be also prevented. The upper sidewall of the columnar silicon layer **113** is covered with the first insulating film sidewall **134**, thereby it is possible to prevent the formation of metal-silicon compounds in the sidewall of the columnar silicon layer **113**.

[0067] Referring to FIG. 33, a dopant such as P or As is implanted into the upper part of the columnar silicon layer **113** by a common method of dopant implantation to form a drain diffusion layer **201**. A body **309** is formed between the source diffusion layer **200** and the drain diffusion layer **201**.

[0068] Referring to FIG. 34, a first metal film is formed on the resultant structure of the above steps by sputtering metal such as Ni or Co. Then, the substrate is treated with heat to produce a metal-semiconductor compound on the surfaces of the source diffusion layer **200** and drain diffusion layer **201**. Any un-reacted metal film is removed to form a metal-semiconductor compound layer **152** on the drain diffusion layer **201** and a metal-semiconductor compound layer **153** on the source diffusion layer **200**. In this step, a metal-silicon compound layer **151** is also

formed in the top parts of the gate electrode **141a** and gate wire **141b** surrounding the columnar silicon layer **113**.

[0069] With a metal-silicon compound layer **151** being formed on the gate electrode **141a** surrounding the columnar silicon layer **113**, the parasitic resistance of the gate electrode **141a** is reduced.

[0070] Referring to FIG. 35, a contact stopper film **135** such as a nitride film is formed on the resultant structure of the above steps.

[0071] Referring to FIG. 36, a contact interlayer film **126** such as an oxide film is formed so as to immerse the resultant structure of the above steps, and then is flattened by CMP.

[0072] Referring to FIG. 37, the first resist is applied to the top of the contact interlayer film **126**. Then, the applied first resist is patterned using lithography to form a first pattern **180** corresponding to the area where a contact layer is to be formed on the top of the columnar silicon layer **113**.

[0073] Referring to FIG. 38, the contact interlayer film **126** is etched using the first pattern **180** to form a first contact hole **181** for a contact layer (first contact layer) on the columnar silicon layer **113**. The shape of the first contact hole **181** will be described later. By using the etching condition with a high selectivity ratio between the contact interlayer film **126** that is an oxide film and the contact stopper film **135** that is a nitride film, it is possible to stop etching at the contact stopper film **135**.

[0074] Referring to FIG. 39, a second resist is applied to the resultant structure of the above steps. Then, the applied second resist is patterned using lithography to form a second pattern **182** corresponding to the area where the contact layer (second contact layer) is to be formed on the planar silicon layer and the area where the contact layer (third contact layer) is to be formed on the gate wire **141b**.

[0075] Referring to FIG. 40, the contact interlayer film **126** is etched using the second pattern **182** to form a second contact hole **183** for a contact layer (second contact layer) on the source diffusion layer **200** of the planar silicon layer **112** and a third contact hole **184** for a

contact layer (third contact layer) on the gate wire **141b**. Here, if the contact holes **183** and **184** are so formed as to have sidewalls nearly perpendicular to the substrate **110**, the deepest contact hole **183** can reliably be opened for the contact layer on the source diffusion layer **200** in the planar silicon layer **112**, and the contact resistance of the contact layer formed can be stable. By using etching conditions with a high selectivity ratio between the contact interlayer film **126** and the contact stopper film **135**, it is possible to stop etching at the contact stopper film **135**.

[0076] Referring to FIG. 41, the contact stopper film **135** remaining at the bottoms of the first contact hole **181** on the columnar silicon layer **113**, the second contact hole **183** on the source diffusion layer **200** of the planar silicon layer **112**, and the third contact hole **184** on the gate wire **141b** are removed by etching, respectively.

[0077] Referring to FIG. 42, a barrier metal layer **171** such as tantalum (Ta) and tantalum nitride (TaN) is formed by applying a barrier metal in the contact holes **181**, **183** and **184**, and then a metal film **170** is formed by sputtering or plating a metal as copper (Cu). And, a third contact layer **172** is formed on the gate wire **141b**, a first contact layer **173** is formed on the columnar silicon layer **113** and a second contact layer **174** is formed on the source diffusion layer **200** of the planar silicon layer **112** by CMP. The barrier metal can be titanium (Ti) or titanium nitride (TiN) or even tungsten (W). Alternatively, a copper-containing alloy can be used as the barrier metal.

[0078] Referring to FIGS. 43 and 44, a resist (not shown) is applied. And, the applied resist is patterned using lithography to form a pattern corresponding to the area where the first layer wires **177**, **178**, and **179** are to be formed. Then, a barrier metal layer **175** and a metal layer **176** are formed using this pattern. Through this step, the first layer wires **177**, **178** and **179** are formed.

[0079] In the above production method, the third contact hole **184** on the gate wire **141b** is formed in the same step as the second contact hole **183** on the planar silicon **112**, but the contact hole **184** on the gate wire **141b** may be formed in the same step as the contact hole **181** on the columnar silicon layer **112**.

[0080] The relationship in shape between the contact layer **173** on the columnar silicon layer **113** and the upper part of the columnar silicon layer **113** in the present embodiment will be described in detail hereafter. In an SGT as used in the present embodiment, short channel effect can be prevented more effectively as the columnar silicon layer **113** is smaller. Accordingly, the columnar silicon layer **113** is patterned with a mostly minimum size by lithography. The columnar silicon layer **113** is then reduced in size in dimensional shrinkage during etching and sacrificial oxidation. Consequently, the final size of the columnar silicon layer **113** is smaller than the minimum patternable size. Accordingly, the bottom of the contact layer **173** on the columnar silicon layer **113** is often larger in size than the upper part of the columnar silicon layer **113**.

[0081] FIG. 45 A and 45B show cross-sectional views around the upper part of the columnar silicon layer **113** after the contact interlayer film **126** is etched. FIGS. 45A and 45B show comparison examples of the semiconductor device according to the first embodiment and the production method thereof in order to explain the semiconductor device of the first embodiment and production method thereof.

[0082] As shown in FIG. 45A, the bottom of the first contact hole **181** is larger in size than the top surface of the contact stopper film **135** formed on the top part and side surface of the columnar silicon layer **113**. In this comparison example, the first contact hole **181** on the columnar silicon layer **113** reaches the surface of the gate wire **141b** after etching the contact stopper film **135** as shown in FIG. 45B. That leads to a short circuit between the first contact layer **173** and the gate wire **141b**. Therefore, in order to prevent short circuit between the gate wire **141b** and the first contact layer **173** on the columnar silicon layer **113**, the bottom of the first contact layer **173** must be smaller in size than the top surface of the contact stopper film **135** formed on the top part and upper sidewall of the columnar silicon layer **113**.

[0083] FIGS. 46A to 48C are enlarged views around the upper part of the columnar silicon layer **113** after the contact interlayer film **135** is etched. FIGS. 46A and 47A are plane schematic diagrams. FIGS. 46B and 46C are enlarged cross-sectional views around the upper part of the

columnar silicon layer **113** along a cut line A-A' in FIG. 46A. FIGS. 47B, 47C and 48A to 48C are enlarged cross-sectional views around the upper part of the columnar silicon layer **113** along the cut line A-A' in FIG. 47A. FIGS. 46A and 47A are planar schematic diagrams, but hatching is applied in some parts in order to differentiate the areas.

[0084] FIGS. 46A and 46B are views around the upper part of the columnar silicon layer **113** when the bottom surface of the contact hole **181** is smaller in size than the top surface of the contact stopper film **135** formed on the top surface and upper sidewall of the columnar silicon layer **113**. That is, the projection **181a** of the bottom surface of the first contact hole **181** for the first contact layer **173** onto the substrate **110** is within the circumference **135a** of the projected profile of the contact stopper film **135** on the substrate **110**. The contact stopper film **135** is formed on the top surface and upper side surface of the columnar silicon layer**113**. In this case, the film thickness of the contact stopper film **135** is thicker in the vertical direction from the surface of the gate electrode **141a** to the bottom surface of the first contact hole **181** for the first contact layer **173** than that of the contact stopper film **135** from the top surface of the columnar silicon layer **113** to the bottom surface of the first contact hole **181**. Therefore, short circuit does not easily occur between the gate electrode **141a** and the first contact layer **173** even if almost 100% over-etching occurs. Accordingly, the first contact hole **181** is formed so that the projection of the first contact hole **181** onto the substrate **110** is within the circumference of the projected profile onto the substrate **110** of the contact stopper film **135** formed on the top surface and upper sidewall of the columnar semiconductor layer **113**.

A modification of this embodiment is shown in FIG. 46C. As shown in FIG. 46C, by forming the first contact hole **181** so that the bottom surface is smaller than the top surface, it is possible for the projection of the bottom surface of the first contact hole **181** onto the substrate **110** to be within the circumference of the projected profile onto the substrate **110** of the contact stopper film **135** formed on the top surface and upper sidewall of the columnar semiconductor layer **113**.

According to this structure, it is possible to prevent short circuits between the first

contact layer **173** on the columnar semiconductor layer **113** and the gate electrode **141a** formed around the columnar semiconductor layer **113**.

[0085] Another modification of the present embodiment is shown in FIG. 47B. The contact stopper film **135** formed on the top surface and upper sidewall of the columnar semiconductor layer **113** usually has a top surface rounded as shown in FIG. 47B, not right-angled. The etching selectivity ratio is low at the rounded top surface of the contact stopper film **135** when the contact stopper film **135** is composed of a nitride film and the contact interlayer film **126** is composed of an oxide film. Therefore, the contact stopper film **135** may further be etched at the rounded top surface when the contact interlayer film **126** is etched. For this reason, the bottom surface of the first contact hole **181** is made smaller in size than the top surface of the contact stopper film **135** formed on the top part and upper sidewall of the columnar silicon layer **113** and the first contact hole **181** is so formed as to have a bottom surface smaller than the top surface as shown in FIG. 47Aand 47B. As a result, the bottom surface of the contact hole **181** is formed on a relatively flat area of the top surface of the contact stopper film **135**, so a high selectivity ratio is obtained between the contact interlayer film **126** and the contact stopper film **135** during the etching of the contact interlayer film **126**. This leads to reducing the amount of the contact stopper film **135** etched. According to this structure, it is possible to prevent short circuit between the first contact layer **173** and the gate electrode **141a** effectively. Such short circuit can be prevented more effectively as the average inclination of the side surface of the first contact hole **181** is increased. Particularly, when the bottom surface of the first contact hole **181** on the columnar silicon layer **113** is smaller in size than the first insulating film sidewall **134** formed on the upper sidewall of the columnar silicon layer **113**, in other words when the projection **181a** of the first contact hole **181** onto the substrate **110** is within the circumference **134a** of the projected profile of the first insulating film sidewall **134** onto the substrate **110**, the bottom surface of the first contact hole**181** is formed in an area where the contact stopper film **135** has a flat top surface. As a result, short circuit between the first contact layer **173** and the gate electrode **141a** does not easily occur.

[0086] More precisely, even if an attempt is made to form a contact hole having a side surface perpendicular to the substrate **110**, the contact hole may have a bottom surface slightly smaller than the top surface because of the property of etching, and thus the bottom surface becomes smaller as the contact hole is deeper. Therefore, it is sufficient that the average inclination of the side surface of the first contact hole **181** is larger than the average inclination of the side surface of the second contact hole **183** so formed as to have a side surface nearly perpendicular to the substrate.

[0087] Another Embodiment

FIGS. 48A to 48C illustrate the shape of the first contact hole **181** of a semiconductor device according to another embodiment of the present application. Referring to FIGS. 46A to 47B, an explanation is given for when the side surface of the first contact hole **181** is nearly perpendicular to the substrate **110** and for when the cross-section of the first contact hole **181** has a tapered shape, respectively. In this embodiment, the cross-section of the first contact hole **181** may also have the shape shown in FIGS. 48A to 48C. In these cases, when the angle θ made between the line α-β and the perpendicular line to the substrate **110** in FIG. 48A, 48B and 48C is defined as the average inclination of the side surface of a contact hole, it is sufficient that the average inclination of the side surface of the first contact hole **181** is larger than the average inclination of the side surface of the second contact hole **183** so formed as to have a sidewall nearly perpendicular to the substrate **110**.

[0088] Since the first contact hole **181** is shallower than the second contact hole **183** on the planar silicon layer **112**, problems such as premature stopping of etching and varied resistance values do not easily occur. Consequently, by adjusting etching conductions, it is relatively easy to form the first contact hole **181** so that the average inclination of the side surface of the first contact hole **181** is larger than the average inclination of the side surface of the second contact hole **183** that is so formed as to have a side surface nearly perpendicular to the substrate **110**.

[0089] In another modification, the same effect as the above can be obtained by forming the first contact hole **181** on the columnar silicon layer **113** to have a side surface perpendicular to

the substrate **110** and have a small bottom surface, instead of forming the first contact hole **181** so that the average inclination of the side surface of the first contact hole **181** is larger than the average inclination of the side surface of the second contact hole **183** that is so formed that the side surface of the second contact hole **183** is nearly perpendicular to the substrate **110**. As in the above embodiment, particularly when the bottom surface of the first contact hole **181** on the columnar silicon layer **113** is smaller in size than the circumference of the first insulating film sidewall **134** formed on the upper sidewall of the columnar silicon layer **113**, in other words when the projection of the bottom surface of the first contact layer **173** onto the substrate **110** is within the circumference of the projected profile of the first insulating film sidewall **134** on the substrate **110**, the bottom surface of the first contact hole **181** is formed in an area where the contact stopper film **135** has a flat top surface, so short circuit between the first contact layer **173** and the gate electrode **141a** does not easily occur. Since the first contact hole **181** on the columnar silicon layer **113** is shallower than the second contact hole **183** on the source diffusion layer **200** of the planar silicon layer **112**, it is easy to pattern the first contact hole **181** smaller than the other deeper contacts. Here, a smaller contact layer can be patterned by forming a contact interlayer film **126** as thin as possible.

[0090] As described above, the first contact layer **173** on the columnar silicon layer **113** is shallower than the second contact layer **174** on the source diffusion layer **200** in the planar silicon layer **112** and therefore it is easy to form the first contact layer **173**. Consequently, a stable contact resistance can be obtained even if the first contact layer **173** is small in size. On the other hand, the second contact layer **174** is deeper than the first contact layer **173** on the columnar silicon layer **113**. Therefore, the bottom of the second contact layer **174** becomes small when the second contact layer **174** on the source diffusion layer **200** of the planar silicon layer **112** is formed in a tapered shape. Consequently, inconveniences such as the second contact layer **174** having a high resistance and variance in contact resistance becoming large easily occur. For this reason, a second contact hole **183** on the planar silicon layer **112** is preferably formed to have a side surface nearly perpendicular to the substrate **110**, and thereby the bottom

surface area of the second contact hole **183** is maintained. In addition, a first contact hole **181** on the columnar silicon layer **113** is formed to have a smaller bottom surface than that of the second contact hole **183**. According to such a structure, it is possible to prevent short circuits between the first contact layer **173** on the columnar silicon layer **113** and the gate electrode **141a** and gate wire **141b** and to obtain stable resistance of the second contact layer **174** on the source diffusion layer **200** of the planar silicon layer **112**.

[0091] When the first insulating film sidewall **134** is composed of an oxide film, not only short circuit between the first contact layer **173** on the columnar silicon layer **113** and the gate electrode **141a** but also etching of the sidewall of the columnar silicon layer **113** can be prevented. When the first insulating film sidewall **134** is composed of a nitride film, excess etching may occur in the upper sidewall of the columnar silicon layer **113**. On the other hand, when the first insulating film sidewall **134** is composed of an oxide film, excess etching on the upper sidewall of the columnar silicon **113** can be prevented by using conditions yielding a high selectivity ratio between nitride films and oxide films during etching the contact stopper film **135**, which is a nitride film.

[0092] In the above embodiments, the contact interlayer film **126** is an oxide film and the contact stopper film **135** is a nitride film. It is also possible that the contact interlayer film **126** is another insulating film such as a low-k film. In this case, the contact stopper film **135** may be another insulating film for which a high selectivity ratio is available against the insulating film comprising the contact stopper film **135** such as a low-k film.

[0093] In the above embodiment, a planar semiconductor layer **112** is formed on the substrate **110**. It is obvious to a person of ordinary skill in the field that it is possible to form a planar semiconductor layer above a substrate via one or more layers formed on the substrate. The planar semiconductor layer, for example, may be formed on an insulating layer arranged on the substrate, such as an SOI substrate which has an insulating film on a substrate.

[0094] In the above embodiments, the materials and shape of parts are arbitrary, and the specific detailed structure and the like can be modified as appropriate.

[0095] Having described and illustrated the principles of this application by reference to one or more preferred embodiments, it should be apparent that the preferred embodiments may be modified in arrangement and detail without departing from the principles disclosed herein and that it is intended that the application be construed as including all such modifications and variations insofar as they come within the spirit and scope of the subject matter disclosed herein.

[Explanation of Reference Numerals]

[0096]

110 silicon substrate

112 planar silicon layer

113 columnar silicon layer

120 filler oxide film

121 pad oxide film

123 sacrificial oxide film

124 gate insulating film

125 first oxide film

126 contact interlayer film

130 first nitride film

131a second nitride film

131 third insulating film sidewall

132 third insulating film

133 second insulating film sidewall

134 first insulating film sidewall (oxide film)

135 contact stopper film

135a circumference of projected profile of contact stopper film on substrate

140 first amorphous silicon film

141 second amorphous silicon film (gate insulating film)

141a gate electrode

141b gate wire

150, 160, 301 resist pattern

151-153 metal-silicon compound layer

161 antireflection coating (BARC) layer

170 metal film

171 barrier metal layer

172 third contact layer

173 first contact layer

174 second contact layer

175 barrier metal layer

176 metal layer

177, 178, 179 first layer wire

180 first pattern

181 first contact hole

181a projection of bottom surface of first contact hole onto substrate

182 second pattern

183 second contact hole

184 third contact hole

200 source diffusion layer

201 drain diffusion layer

303 first insulating film

303a, 303b, 306 insulating film

305 fourth oxide film

307 offset spacer

309 body

Claims

1. A method of producing a semiconductor device comprising:

a step of preparing a structure provided with a substrate, a planar semiconductor layer formed above the substrate, and a columnar semiconductor layer formed on the planar semiconductor layer;

a step of forming a first source or drain region in a lower part of the columnar semiconductor layer and in the planar semiconductor layer;

a step of forming a gate insulating film around the columnar semiconductor layer;

a step of forming a gate electrode on the gate insulating film so as to surround the columnar semiconductor layer;

a second drain or source region forming step of forming a second drain or source region in an upper part of the columnar semiconductor layer;

a contact stopper film forming step of forming a contact stopper film on a resultant product of the second drain or source region forming step;

a step of forming a contact interlayer film on the contact stopper film so as to embed a resultant product of the contact stopper film forming step; and

a contact layer forming step of forming a first contact layer on the second drain or source region,

wherein the contact layer forming step includes

a pattern forming step of forming a first pattern corresponding to a region where the first contact layer is scheduled to be formed, on the contact interlayer film;

a contact hole forming step of etching the contact interlayer film up to the contact stopper film by using the first pattern so as to form a first contact hole for the first contact layer; and

a contact stopper film removing step of removing the contact stopper film remaining on a bottom of the first contact hole through etching, and

wherein a projection plane of a bottom surface of the first contact hole onto the substrate is located within an outer circumference of a projection shape of the contact stopper film which is formed on an upper surface of the columnar semiconductor layer

and an upper side surface of the columnar semiconductor layer, onto the substrate.

2. The method of producing the semiconductor device according to claim 1,

wherein the contact layer forming step further includes a step of forming a second contact layer on the first source or drain region,

wherein the step of forming the second contact layer includes a step of forming a second pattern corresponding to a region where the second contact layer is scheduled to be formed, on the contact interlayer film, a step of etching the contact interlayer film up to the contact stopper film by using the second pattern so as to form a second contact hole for the second contact layer, and a step of removing the contact stopper film remaining on a bottom of the second contact hole through etching,

wherein the second contact hole is formed such that a side surface of the second contact hole is perpendicular to the substrate, and

wherein the first contact hole is formed such that an average tilt of a side surface of the first contact hole is greater than an average tilt of a side surface of the second contact hole.

3. The method of producing the semiconductor device according to claim 1,

wherein the contact layer forming step further includes a step of forming a second contact layer on the first source or drain region, and a step of forming a third contact layer on a gate wire extending from the gate electrode,

wherein the step of forming the second contact layer includes a step of forming a second pattern corresponding to a region where the second contact layer is scheduled to be formed, on the contact interlayer film, a step of etching the contact interlayer film up to the contact stopper film by using the second pattern so as to form a second contact hole for the second contact layer, and a step of removing the contact stopper film remaining on a bottom of the second contact hole through etching,

wherein the step of forming the third contact layer includes a step of forming a third pattern corresponding to a region where the third contact layer is scheduled to be formed, on the contact interlayer film, a step of etching the contact interlayer film up to

the contact stopper film by using the third pattern so as to form a third contact hole for the third contact layer, and a step of removing the contact stopper film remaining on a bottom of the third contact hole through etching,

wherein the second contact hole is formed such that a side surface of the second contact hole is perpendicular to the substrate,

wherein the third contact hole is formed such that a side surface of the third contact hole is perpendicular to the substrate, and

wherein the first contact hole is formed such that an average tilt of a side surface of the first contact hole is greater than an average tilt of a side surface of the second contact hole.

4. The method of producing the semiconductor device according to claim 1,

wherein the contact layer forming step further includes a step of forming a second contact layer on the first source or drain region, and a step of forming a third contact layer on a gate wire extending from the gate electrode,

wherein the step of forming the second contact layer includes a step of forming a second pattern corresponding to a region where the second contact layer is scheduled to be formed, on the contact interlayer film, a step of etching the contact interlayer film up to the contact stopper film by using the second pattern so as to form a second contact hole for the second contact layer, and a step of removing the contact stopper film remaining on a bottom of the second contact hole through etching,

wherein the step of forming the third contact layer includes a step of forming a third pattern corresponding to a region where the third contact layer is scheduled to be formed, on the contact interlayer film, a step of etching the contact interlayer film up to the contact stopper film by using the third pattern so as to form a third contact hole for the third contact layer, and a step of removing the contact stopper film remaining on a bottom of the third contact hole through etching,

wherein the second contact hole is formed such that a side surface of the second contact hole is perpendicular to the substrate,

wherein the first contact hole is formed such that an average tilt of a side surface of

the first contact hole is greater than an average tilt of a side surface of the second contact hole, and

wherein the third contact hole is formed such that an average tilt of a side surface of the third contact hole is greater than the average tilt of the side surface of the second contact hole.

5. The method of producing the semiconductor device according to claim 1,

wherein the contact layer forming step further includes a step of forming a second contact layer on the first source or drain region,

wherein the step of forming the second contact layer includes a step of applying a second resist on the contact interlayer film and patterning the second resist by using lithography so as to form a second pattern corresponding to a region where the second contact layer is scheduled to be formed, and a step of etching the contact interlayer film up to the contact stopper film by using the second pattern so as to form a second contact hole for the second contact layer,

wherein, in the contact layer forming step, a third contact layer is further formed on a gate wire extending from the gate electrode,

wherein, in the pattern forming step, a first resist is applied on the contact interlayer film and the first resist is patterned using lithography such that the first pattern is formed so as to correspond to a region where the first contact layer is scheduled to be formed and a region where the third contact layer is scheduled to be formed,

wherein, in the contact hole forming step, the contact interlayer film is etched up to the contact stopper film by using the first pattern so as to form the first contact hole and a third contact hole for the third contact layer,

wherein the contact stopper film removing step is performed after the first contact hole, the second contact hole, and the third contact hole are formed,

wherein, in the contact stopper film removing step, the contact stopper film remaining on respective bottoms of the first contact hole, the second contact hole and the third contact hole is removed through etching,

wherein the second contact hole is formed such that a side surface of the second

contact hole is perpendicular to the substrate,

wherein the first contact hole is formed such that an average tilt of a side surface of the first contact hole is greater than an average tilt of a side surface of the second contact hole, and

wherein the third contact hole is formed such that an average tilt of a side surface of the third contact hole is greater than the average tilt of the side surface of the second contact hole.

6. The method of producing the semiconductor device according to claim 1,

wherein the contact layer forming step further includes a second and third contact layers forming step of forming a second contact layer on the first source or drain region and forming a third contact layer on a gate wire extending from the gate electrode,

wherein the second and third contact layers forming step includes a step of applying a second resist on the contact interlayer film and patterning the second resist by using lithography so as to form a second pattern corresponding to a region where the second contact layer is scheduled to be formed and a region where the third contact layer is scheduled to be formed, and a step of etching the contact interlayer film up to the contact stopper film by using the second pattern so as to form a second contact hole for the second contact layer and a third contact hole for the third contact layer,

wherein, in the pattern forming step, a first resist is applied on the contact interlayer film and the first resist is patterned using lithography so as to form the first pattern corresponding to a region where the first contact layer is scheduled to be formed,

wherein the contact stopper film removing step is performed after the first contact hole, the second contact hole, and the third contact hole are formed,

wherein, in the contact stopper film removing step, the contact stopper film remaining on respective bottoms of the first contact hole, the second contact hole and the third contact hole is removed through etching,

wherein the second contact hole is formed such that a side surface of the second contact hole is perpendicular to the substrate,

wherein the third contact hole is formed such that a side surface of the third contact

hole is perpendicular to the substrate,

wherein the first contact hole is formed such that an average tilt of a side surface of the first contact hole is greater than an average tilt of a side surface of the second contact hole, and

wherein the first contact hole is formed such that an average tilt of a side surface of the first contact hole is greater than an average tilt of a side surface of the third contact hole.

7. The method of producing the semiconductor device according to claim 1, further comprising:

an oxide film forming step of forming an oxide film in a sidewall shape on the upper side surface of the columnar semiconductor layer after the gate electrode is formed and before the second drain or source region is formed,

wherein the contact stopper film is a silicon nitride film.

8. A semiconductor device comprising:

a substrate;

a planar semiconductor layer formed on the substrate;

a columnar semiconductor layer formed on the planar semiconductor layer;

a first source or drain region formed on a bottom of the columnar semiconductor layer;

a second drain or source region formed in an upper part of the columnar semiconductor layer;

a gate insulating film formed around the columnar semiconductor layer;

a gate electrode formed on the gate insulating film so as to surround the columnar semiconductor layer;

a first contact layer formed on the second drain or source region;

a second contact layer formed on the first source or drain region; and

a third contact layer formed on a gate wire extending from the gate electrode,

wherein a side surface of the second contact layer is perpendicular to the substrate,

and

wherein an average tilt of a side surface of the first contact layer is greater than an average tilt of a side surface of the second contact layer.

9. The semiconductor device according to claim 8,

wherein an average tilt of a side surface of the third contact layer is greater than the average tilt of the side surface of the second contact layer.

10. The semiconductor device according to claim 8,

wherein a side surface of the third contact layer is perpendicular to the substrate, and

wherein an average tilt of the side surface of the first contact layer is greater than an average tilt of a side surface of the third contact layer.

11. A semiconductor device comprising:

a substrate;

a columnar semiconductor layer formed over the substrate;

a first source or drain region formed on a bottom of the columnar semiconductor layer;

a second drain or source region formed in an upper part of the columnar semiconductor layer;

a gate insulating film formed around the columnar semiconductor layer;

a gate electrode formed on the gate insulating film so as to surround the columnar semiconductor layer;

a first contact layer formed on the second drain or source region;

a second contact layer formed on the first source or drain region;

a third contact layer formed on a gate wire extending from the gate electrode; and

a first insulating film sidewall formed on an upper side surface of the columnar semiconductor layer,

wherein a projection plane of a bottom surface of the first contact layer onto the

substrate is located within an outer circumference of a projection shape of the first insulating film sidewall onto the substrate.

12. The semiconductor device according to claim 11, further comprising:

a contact stopper film formed on the first insulating film sidewall,

wherein the first insulating film sidewall is a silicon oxide film, and

wherein the contact stopper film is a silicon nitride film.