A resistor has a resistor body (11) of polycrystalline silicon and electrical terminals (23, 15) arranged on and/or in the resistor body (11), so that a resistor portion (13) is formed between the terminals and produces the useful resistance of the resistor. The material of the resistor body is doped with dopants of both acceptor type and donor type. In order to block the charge carrier traps at grain boundaries to a sufficient degree and thereby give the resistor a good stability, also when it is exposed to different substances during the manufacture, the doping is made with donors in such a high concentration, that if only the donor atoms would be present in the material and substantially no acceptor atoms, the material would be to be considered as more or less heavily doped. In particular donor atoms are to be provided in the resistor body in a concentration of at least $3 \times 10^{19} \text{ cm}^{-3}$, in the case where the material has an average grain size of 1000 Å and phosphorus is used as a dopant of donor type.
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A POLYSILICON RESISTOR AND A METHOD OF MANUFACTURING IT
TECHNICAL FIELD
The invention relates generally to electronic components, primarily such that are used in electronic integrated circuits and/or are manufactured by means of the corresponding processing methods, and in particular electric resistors made of polycrystalline silicon and a method of manufacturing such resistors.

BACKGROUND AND STATE OF THE ART
In for example analog electronic circuits used in telecommunication systems the requirements for stability of included resistors are extremely high. The stability requirements can be expressed by stating that the absolute values of the resistances must be lower than limit values of maximum allowed change and/or by stating that possible changes of the resistances of resistors included in a group of matched resistors must be such that the ratios of the magnitude of the resistances in relation to each other do not deviate more than some limit value. A type of resistors that can be suitable is based on polycrystalline silicon ("polysilicon"). They can be manufactured by means of methods generally used within the field of manufacturing electronic integrated circuits.

Resistors of polycrystalline silicon have been used within the electronics field during a time of about 30 years. Methods of manufacturing polycrystalline silicon are well known and it is also known that the resistivity of polysilicon can be controlled to a desired value by adding dopants to the polysilicon, see "Polycrystalline Silicon for Integrated Circuit Applications", T. Kamins, Kluver Academic Publishers, 1988.

A known problem in resistors of polysilicon is their stability that is not always satisfactory. Such resistors change easily their resistance values during the various steps that are executed in the manufacturing operation and during the final use in a real electronic circuit. Of course, such deviations from the intended values can jeopardize the operation of the electronic circuit in which the resistors are included. The cause of instability is to be looked for in the unsaturated, "dangling", bonds that exist in the grain boundaries of the polysilicon. The unsaturated bonds work as traps for the charge carriers and bind thereby charges to the grain boundaries, influencing the capability of the material of transporting charge carriers and thereby the resistivity of the material and the overall resistance of a polysilicon resistor.

Compensation doping has been used for producing polysilicon resistors that are less sensitive to variations in the dopant concentration and have a lower temperature coefficient than polycrystalline films doped with only one dopant, see the published European patent application EP-A2 0 145 926, which is incorporated by reference herein. According to the method proposed in this document a polysilicon film is given a background doping with boron, i.e. of p-type, after which a compensation doping of n-type with phosphorus is
executed so that the material obtains a net p-doping. A reduction of the resistivity dependence on the dopant concentrations are thereby obtained and also of its dependence on temperature. The background doping with boron is made with concentrations not exceeding $5 \times 10^{19}$ cm$^{-3}$ and the compensation doping of n-type with the specified concentrations at most comprising $2.9 \times 10^{18}$ cm$^{-3}$. Compare also the article by J.B. Kim and M.S. Choi, Journal of Korean Institute of Electronic Engineering, No. 24, p. 81, 1987.

When adding hydrogen atoms to doped polysilicon they can react with the unsaturated bonds in polycrystalline silicon and block them so that they cannot any longer serve as traps for charge carriers. However, a problem of hydrogen atoms that have been bound to unsaturated bonds is that their bonding strength is low. The bonds of the hydrogen atoms to the silicon atoms can therefore be broken at an increased temperature, and hydrogen will then diffuse out from the grain boundaries. The resistance of a body of silicon processed with or subjected to hydrogen is then changed in an uncontrollable way. Such increased or elevated temperatures occur during the manufacturing steps of a polysilicon resistor and when using a polysilicon resistor in a real electronic circuit.

Moreover, hydrogen is included in a significant amount (typically 20 - 25%) in the passivating films of silicon nitride produced by means of plasma CVD that are conventionally used as a protection for finished integrated circuits and components.

Also other kinds of atoms that are used in the various processing steps for manufacturing a polysilicon resistor can be bound to the rather reactive, unsaturated dangling bonds in the grain boundaries and influence the stability of the finished resistor.

DESCRIPTION OF THE INVENTION
The problem to be solved by the invention is thus how to provide and how to manufacture polysilicon resistors having a high or sufficient stability to be used e.g. in analog electronic circuits and thus how to ensure that the resistance values for instance do not change in an uncontrollable way during manufacture and/or use.

The solution of the problem presented above in regard of stability of polysilicon resistors is that it should be achieved that the unsaturated bonds in the grain boundaries are blocked in such a way that can be considered, considering the conditions in the manufacture and the use of the circuit, to be more or less permanent. Such a blocking operation appears to be produced by adding donor atoms, like the known methods, to the polycrystalline silicon material but in a considerably higher concentration. During the heat treatment steps that are included when manufacturing a resistor, a number of the added donor atoms diffuse to the grain boundaries of the silicon material, where they take positions in such a way that they
block the unsaturated bonds. The latter ones cannot then form the traps for the charge carriers which otherwise would influence the resistivity. The concentration of the added donor atoms should be so large that, in the case where only the donor atoms would be present in the material, it would be considered as more or less heavily doped. For a polycrystalline film having an average grain size of 1000 Å and having primarily a doping with phosphorus this means that the donor concentrations should be at least $3 \cdot 10^{19}$ cm$^{-3}$.

In order to make it possible to set the value of the resistivity to a desired value, also acceptor atoms are added to the silicon material in such a way, that both acceptors and donors exist in the finished polysilicon. The concentration of the acceptors should be such, that it, combined with the added acceptors, produces a net concentration of charge carriers that results in that the material obtains the desired resistivity. Since a part of the donor atoms diffuse out into the grain boundaries and therefore cannot contribute with charge carriers the required concentrations of dopants cannot easily be calculated but the exact concentrations must suitably be determined by experiments.

As acceptor atoms primarily boron and as donor atoms, phosphorus and arsenic can be used. However, it appears that the same blocking effect comprising a similar stability is obtained for all the typical acceptor materials boron, aluminium, gallium or indium, both when they are used alone or in combination with each other. Further, together with arbitrary acceptor material all types of donors, phosphorus, arsenic or antimony can be used alone or in combination with each other. Further it is not critical in which order the donor and acceptor atoms are added to the polysilicon material for forming a resistor. The essential point is only that the minimum concentration of donor atoms is not lower than the level, above which the material, in the case where the material would be doped with only the donor or the donors in question, is to be considered as more or less highly doped. The net concentration of acceptors and donors in the material should be such that the material obtains the desired resistivity and gets the desired p- or n-type.

Further, it is not required that the donor or acceptor atoms during the process which is intended to add the dopant atoms to the polycrystalline silicon are to be used in the shape of pure elements but they can be included in compounds, as long as they have the property that the molecules in these compounds in the introductory process are broken in such a way that the doping atoms can penetrate into the material.

A doping method according to the above is applied primarily for thin polycrystalline films but can equally well be performed for all types of resistors of polycrystalline silicon having arbitrary resistances which is doped with acceptors and donors.
The word resistor here indicates the use of polycrystalline silicon in all applications where the ability of the material to conduct electrical current is used forming a resistance to the current. The donors and/or acceptors can be added to the polycrystalline silicon by means of ion implantation, followed by a heat treatment for healing fault positions and a distribution of dopant atoms to suitable places in the crystal lattice. The dopant atoms can also be added to the material by adding the dopants during the very manufacture of the polycrystalline material or by a subsequent diffusion of the dopants into the polycrystalline material. A method of the latter kind can be executed by heat treating the polycrystalline material in one of several steps in atmospheres containing one or several gases, in the molecules of which the desired donor and acceptor atoms are included. Another way of diffusing the dopant into the material is to coat the surface of the polycrystalline material with materials that contain the desired dopant atoms in such concentrations that these atoms can diffuse into the polycrystalline material in a simultaneous or subsequent heat treatment.

DESCRIPTION OF THE DRAWINGS

The invention will now be described in detail by way of non-limiting embodiments with reference to the accompanying drawings, in which:

- Fig. 1 is a schematic picture of a cross section of a resistor manufactured of a polycrystalline silicon,
- Fig. 2 is a view of a resistor as seen from above where a part of an area that is compensation doped is highly magnified,
- Fig. 3 is a diagram illustrating the result of accelerated load tests of resistors of polycrystalline silicon,
- Fig. 4 is a diagram illustrating the results of measurements of polycrystalline silicon films, which have been heat treated in an atmosphere containing hydrogen.

DESCRIPTION OF PREFERRED EMBODIMENTS

In Fig. 1 an example is shown of a cross section of a polysilicon resistor. It is it produced on a carrier structure 1 that can contain integrated components and at its top carries or connects to an isolating layer 3 of silicon oxide, for example thermal oxide but it can naturally also be deposited. In the embodiment shown, at the bottom of the carrier structure 1, a silicon substrate 5 is arranged, for example a monocrystalline silicon plate, on top thereof a silicon substrate zone 7 having different regions of substances diffused into them, on top thereof a layer structure 9 comprising dielectric materials and polysilicon and on the very top the oxide layer 3. On the oxide layer 3 the very platform or "mesa" 11 is arranged that constitutes the resistor body and that seen from above has for example a rectangular shape, see the view from above of the very resistor body in Fig. 2. The resistor body 11 comprises an inner or
intermediate portion 13, which is the part that gives or determines the resistance of the resistor, and outer regions 15 for contacting that can be strongly highly doped and thereby have a fairly low resistance.

The top surface of the assembly comprising a carrier structure 1 and resistor body 11 is covered with an oxide layer 17 and on top thereof a silicon nitride layer 19, but it is also possible to arrange, on top of the assembly, further layers comprising passive or active electric and electronic devices. Holes 21 are made through these two layers down to the top surface of the contacting regions 15. At the surface of the contacting regions 15 regions 23 are provided inside the holes 21 for improving even more the contact with conductor paths 25 of aluminium for the electrical connection of the resistor. The regions 23 can comprise conductive diffusion barrier layers comprising for example titanium or some titanium compound that is diffused from a coated layer.

In Fig. 2 is also shown, in a highly magnified partial view, a schematic picture of a compensation doped region of a polysilicon resistor. It appears therefrom how acceptors A, donors D, charge carrier traps T and hydrogen atoms H take their positions inside grains 31 or in grain boundaries 33 respectively, compare the discussion above.

The manufacture of polysilicon resistors will now be described with reference to examples. First manufacture of resistors having a single doping will be described hereinafter.

Example 1
20 Polycrystalline films of silicon having a thickness of about 5500 Å were disposed by means of the conventional CVD method (Chemical Vapor Deposition) on top of layer of thermal silicon dioxide having a thickness of 9000 Å. On top of the polysilicon film silicon dioxide was deposited having a thickness of about 5500 Å, again by means of CVD. After that a heat treatment was performed at 1050°C during 30 minutes that among other things defines the grain size of the polysilicon. The surface of the polysilicon was etched to be free from oxide, after which boron was implanted to a concentration of 1·10¹⁹ cm⁻³ in the film at an energy of 80 keV. Thereafter a lithographically defined mask was placed on the polysilicon and the resistors were etched so that they obtained a length of 200 μm and a width of 20 μm. After that silicon dioxide was deposited to a thickness of 6500 Å at 400°C by means of CVD,

30 followed by a heat treatment at 1000°C during about 45 minutes. It was followed by a process flow that is normal within the technical field of manufacturing electronic integrated circuits, comprising etching contact holes, metallization, lithographic definition of conductive paths, alloying in hydrogen gas at 420°C during 20 minutes and a passivation by means of a layer of silicon nitride having a thickness of 9000 Å. The last mentioned layer was produced
by means of Plasma Enhanced CVD (PECVD). The polycrystalline film was of p-type and had a resistivity of 605 ohm/square.

The resistors were mounted in the conventional manner in ceramic capsules and were then subjected to accelerated heat stress tests at 98°C and 150°C and with an electric voltage of 30 V applied over the resistors, during a time period of up to 1000 h, the resistances of the resistors being measured after 0, 168, 500, and 1000 h. The results are illustrated for the higher temperature, 150°C, by the curve drawn as a solid line in the diagram of Fig. 3. As appears from the figure, the resistances of the resistors increased by 2%, compared to the resistance values at the start of the test process. Resistors having such large changes are generally not suited to be used for example in analog circuits.

Further, resistors were manufactured of polycrystalline silicon having a double doping, that is having a compensation doping, for blocking the charge carrier traps in the grain boundaries as mentioned above. Primarily experiments were made where the concentrations of the added donor atoms were fairly high. Actually, it appeared that the concentration of the donor atoms should be so great, that if only they would exist in the material, the material would be considered as essentially heavily doped. For a polycrystalline film having an average grain size of 1000 Å, it means that the donor concentration should be at least $3 \cdot 10^{19}$ cm$^{-3}$.

**Example 2**

On polycrystalline silicon films, manufactured according to example 1, boron was implanted in a dose of $8 \cdot 10^{19}$ cm$^{-3}$ at 80 keV, followed by an implantation of phosphorus to a dose of $13.6 \cdot 10^{19}$ cm$^{-3}$ at 120 keV. From the obtained polysilicon film resistors were produced in the same way as in example 1. The polycrystalline film in the resistors was of n-type and had a resistivity of 1020 ohm/square.

The resistors were mounted in ceramic capsules and were thereafter exposed to accelerated heat stress tests at 98 and 150°C up to 1000 h. The change of the resistances at the high temperature is illustrated by the curve 2 drawn as a dotted line in Fig. 3, from which it appears that the resistances of the resistors increased by less than 1% compared to the resistance values at the start of the test. It illustrates the stabilizing effect that is obtained in the case where the resistors are manufactured according to the method described here.

**Example 3**

On polycrystalline silicon films, manufactured according to example 1, the silicon surface was etched to be freed of oxide, after which boron was implanted to a dose of $4 \cdot 10^{19}$ cm$^{-3}$ at 80 keV followed by an implantation of arsenic to a dose of $9.6 \cdot 10^{19}$ cm$^{-3}$ at 120 keV.
From the obtained polysilicon film resistors were produced according to example 1. The polycrystalline film in the resistors was of n-type and had a resistivity of 699 ohms/square.

The resistors were mounted in ceramic capsules and were after that exposed to accelerated heat stress tests at 98 and 150°C up to 1000 h. It appeared that these resistors changed by approximately the same amount as the resistors in example 2 that were doped with boron and with phosphorus.

Example 4
On polycrystalline silicon films, manufactured according to example 1, the silicon surface was etched to be free from oxide, after which boron was implanted to a dose of $8 \cdot 10^{19}$ cm$^{-3}$ at 80 keV, followed by an implantation of phosphorus to a dose of $5 \cdot 10^{19}$ cm$^{-3}$ at 120 keV. From the obtained polysilicon film resistors were produced according to example 1. The polycrystalline film in the resistors was of p-type and had a resistivity of 241 ohm/square.

The resistors were mounted in ceramic capsules and were exposed after that to accelerated heat stress tests at 98 and 150°C up to 1000 h. It appeared that these resistors changed by approximately the same amount as the resistors in example 1 that were doped with boron and with phosphorus.

Since hydrogen is included in the passivating films of silicon nitride which are produced by means of plasma enhanced CVD it is important that the produced films do not change their resistance values or obtain a reduced stability when they are exposed to hydrogen gas atmosphere, compare the discussion above. A number of films which were manufactured according to the examples above, were therefore exposed to a hydrogen gas atmosphere consisting of 10% hydrogen gas by volume mixed with 90% nitrogen gas at accelerated testing at 420°C during 20 minutes. The resistances were determined before and after the hydrogen gas treatment and the measured changes of the resistances in relation to the resistance values at the start of the test were calculated. In the diagram of Fig. 4 the results of the measurements are shown. The largest change is presented by the films according to example 1, curve 1 in Fig. 4, which were singly doped. Curve 2 in Fig. 4 shows the result for a film that certainly has been compensation-doped with boron and phosphorus but where the phosphorus concentration has been too small. Only for a concentration of phosphorus atoms exceeding $3 \cdot 10^{19}$ cm$^{-3}$ a significant reduction of the hydrogen sensitivity of the material is obtained, see the curves at 3 in Fig. 4.
CLAIMS

1. A resistor comprising a resistor body of polycrystalline silicon and electric terminals applied to and/or in the resistor body, having a resistor portion between the terminals that produces the resistance of the resistor, the material of the resistor part being doped with dopants of both acceptor type and donor type for producing a desired resistance of the resistor, characterized in that the concentration of the dopant/dopants of donor type in the resistor body is so large that it/they blocks/block charge carrier traps at grain boundaries in the polycrystalline material to such a high extent that the polycrystalline material has a good stability, i.e. changes its resistivity in only a small extent, in particular when it is exposed to substances that can bind to unsaturated bonds in the material.

2. A resistor according to claim 1, characterized in that the concentration of the dopant/the dopants of donor type in the resistor body is so large that, if only they/these would exist in the material and no dopants of acceptor type would be there, it would be considered as substantially heavily doped.

3. A resistor according to one of claims 1 - 2, characterized in that the concentration of the dopant/dopants of donor type in the resistor body is at least 3⋅10^{19} \text{ cm}^{-3}.

4. A resistor according to one of claims 1 - 3, characterized in that the resistor portion comprises polycrystalline silicon having an average grain size of 1000 Å that is doped with phosphorus.

5. A method of manufacturing a resistor comprising a resistor body of polycrystalline silicon comprising the steps of:
   - producing a body, in particular a film, of polycrystalline silicon,
   - doping the material of the body, at the manufacture thereof or thereafter, with dopants of both acceptor type and donor type for producing a desired resistance of the resistor, and
   - arranging electrical contact terminals to the body,
characterized in that in the doping step the dopant/dopants of donor type is/are added to the resistor body in such a concentration that it/they block the charge carrier traps at grain boundaries in the polycrystalline material to such a high extent that the polycrystalline material presents a good stability, i.e. changes its resistivity in only a small degree, in particular when it is exposed to substances that can bind to unsaturated bonds in the material.

6. A method according to claim 5, characterized in that in the doping step the dopant/dopants of donor type is/are added to the resistor body in such a concentration that if only it/they would exist in the material in the body and no dopants of acceptor type were to exist therein, the material of the body would be considered as essentially heavily doped.
7. A method according to one of claims 5 - 6, characterized in that in the doping step the dopant/dopants of donor type is/are added to the resistor body in such an amount that the concentration of the dopant/dopants of donor type in the resistor body is at least $3 \times 10^{19}$ cm$^{-3}$.

8. A method according to one of claims 5 - 7, characterized in that in the manufacture of the resistor body it is treated so that it obtains an average grain size of 1000 Å and that in the dopant step phosphorus is used as dopant of donor type.
Fig. 1

Fig. 2

Polysilicon resistor

---

23

11

31

33
Fig. 3

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Fig. 4

Rs [rel. unit]

After annealing

After $H_2$ heat treatment
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

IPC6: H01C 7/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC6: H01C, H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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March 2, 1997

Date of the actual completion of the international search

Date of mailing of the international search report

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