LOW-TEMPERATURE POST-DOPANT ACTIVATION PROCESS

FIELD OF THE INVENTION

The present invention relates to the manufacturing of semiconductor devices, and more particularly, to post-laser anneal processes that prevent dopant deactivation.

BACKGROUND OF THE INVENTION

Over the last few decades, the semiconductor industry has undergone a revolution by the use of semiconductor technology to fabricate small, highly integrated electronic devices, and the most common semiconductor technology presently used is silicon-based. A large variety of semiconductor devices have been manufactured having various applications in numerous disciplines. One silicon-based semiconductor device is a metal-oxide-semiconductor (MOS) transistor. The MOS transistor is one of the basic building blocks of most modern electronic circuits. Importantly, these electronic circuits realize improved performance and lower costs, as the performance of the MOS transistor is increased and as manufacturing costs are reduced.

A typical MOS semiconductor device generally includes a semiconductor substrate on which a gate electrode is disposed. The gate electrode, which acts as a conductor, receives an input signal to control operation of the device. Source and drain regions are typically formed in regions of the substrate adjacent the gate electrodes by doping the regions with a dopant of a desired conductivity. The conductivity of the doped region depends on the type of impurity used to dope the region. The typical MOS transistor is symmetrical, in that the source and drain are interchangeable. Whether a region acts as a source or drain typically depends on the respective applied voltages and the type of device being made. The collective term source/drain region is used herein to generally describe an active region used for the formation of either a source or drain.

MOS devices typically fall in one of two groups depending the type of dopants used to form the source, drain and channel regions. The two groups are often referred to as n-channel and p-channel devices. The type of channel is identified based on the conductivity type of the channel which is developed under the transverse electric field. In an n-channel MOS (NMOS) device, for example, the conductivity of the channel under a transverse electric field is of the conductivity type associated with n-type impurities (e.g., arsenic or phosphorous). Conversely, the channel of a p-channel MOS (PMOS) device under the transverse electric field is associated with p-type impurities (e.g., boron).

A type of device, commonly referred to as a MOS field-effect-transistor (MOSFET), includes a channel region formed in the semiconductor substrate beneath the gate area or electrode

and between the source and drain regions. The channel is typically lightly doped with a dopant having a conductivity type opposite to that of the source/drain regions. The gate electrode is generally separated from the substrate by an insulating layer, typically an oxide layer such as SiO_2. The insulating layer is provided to prevent current from flowing between the gate electrode and the source, drain or channel regions. In operation, a voltage is typically developed between the source and drain terminals. When an input voltage is applied to the gate electrode, a transverse electric field is set up in the channel region. By varying the transverse electric field, it is possible to modulate the conductance of the channel region between the source and drain regions. In this manner an electric field is used to control the current flow through the channel region.

The semiconductor industry is continually striving to improve the performance of MOSFET devices. The ability to create devices with sub-micron features has allowed significant performance increases, for example, from decreasing performance degrading resistances and parasitic capacitances. The attainment of sub-micron features has been accomplished via advances in several semiconductor fabrication disciplines. For example, the development of more sophisticated exposure cameras in photolithography, as well as the use of more sensitive photoresist materials, have allowed sub-micron features, in photoresist layers, to be routinely achieved. Additionally, the development of more advanced dry etching tools and processes have allowed the sub-micron images in photoresist layers to be successfully transferred to underlying materials used in MOSFET structures.

As the dimensions of the MOSFET shrinks, the reduction in effective gate length requires a proportional scaling in the vertical junction depth of the source/drain regions. The reduction in the junction depth of the source/drain regions is to reduce short channel effects.

As the distance between the source region and the drain region of the MOSFET (i.e., the physical channel length) decreases, in the effort to increase circuit speed and complexity, the junction depth of source/drain regions must also be reduced to prevent unwanted source/drain-to-substrate junction capacitance. However, obtaining these smaller junction depths tests the capabilities of current processing techniques, such as ion implantation with activation annealing using rapid thermal annealing. Rapid thermal annealing typically involves heating the silicon wafer, after implanting, under high-intensity heat lamps. Implanting or doping creates an amorphitizes the silicon substrate, and the activation annealing is used to recrystallize the amorphitized silicon region.

As a result of the limitations of rapid thermal annealing, laser thermal annealing is being implemented, particularly for ultra-shallow junction depths. Laser thermal annealing may be performed after ion implantation of a dopant and involves heating the doped area with a laser. The laser radiation rapidly heats the exposed silicon such that the silicon begins to melt. The diffusivity

of dopants into molten silicon is about 8 orders of magnitude higher than in solid silicon. Thus, the dopants distribute almost uniformly in the molten silicon and the diffusion stops almost exactly at the liquid/solid interface. The heating of the silicon is followed by a rapid quench to solidify the silicon, and this process allows for non-equilibrium dopant activation in which the concentration of dopants within the silicon is above the solid solubility limit of silicon. Advantageously, this process allows for ultra-shallow source/drain regions that have an electrical resistance about one-tenth the resistance obtainable by conventional rapid thermal annealing.

A problem that exists with this process is that subsequent high-temperature processing can cause the dopants in the source/drain regions to become deactivated. A dopant is deactivated when it is removed from a lattice site, and deactivation of dopants typically occurs at temperature above about 700°C, which occurs with such processes as rapid thermal annealing. Accordingly, a need exists for improved post-dopant activation processes that prevent dopant deactivation.

SUMMARY OF THE INVENTION

This and other needs are met by embodiments of the present invention which provide a method of manufacturing a semiconductor device that reduces dopant deactivation. The method comprises forming a gate electrode over a substrate and forming a gate oxide between the gate electrode and the substrate; forming source/drain extensions in the substrate; forming first and second sidewall spacers; implanting dopants within the substrate to form source/drain regions in the substrate adjacent to the sidewalls spacers; and laser thermal annealing to activate the source/drain regions. A layer of nickel is then deposited over the source/drain regions and annealed at low temperature to reduce dopant deactivation.

In a further aspect of the present invention, the source/drain extensions can have a depth of about 5 to 30 nanometers, and the source/drain regions can have a depth of about 40 to 100 nanometers. Additionally, the temperature at which the nickel silicide is formed is from about 350 to 500°C.

Additional advantages of the present invention will become readily apparent to those skilled in this art from the following detailed description, wherein only the preferred embodiment of the present invention is shown and described, simply by way of illustration of the best mode contemplated for carrying out the present invention. As will be realized, the present invention is capable of other and different embodiments, and its several details are capable of modifications in various obvious respects, all without departing from the invention. Accordingly, the drawings and description are to be regarded as illustrative in nature, and not as restrictive.

BRIEF DESCRIPTION OF THE DRAWINGS

Reference is made to the attached drawings, wherein elements having the same reference numeral designations represent like elements throughout, and wherein:

Figures 1A-1I schematically illustrate sequential phases of a MOS fabrication method using a low-temperature salicide process in conjunction with a laser thermal annealing activation process according to an embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

The present invention addresses and solves the problem of dopant deactivation as a result of high-temperature post-dopant activation processes, such as rapid thermal annealing. This is achieved, in part, by activating source/drain regions using laser thermal annealing, which is followed by a low-temperature salicide formation process. In particular, nickel silicide is formed over the activated source/drain region by applying a nickel layer over the source/drain region followed by a low-temperature furnace anneal. The temperature is sufficiently high to produce nickel silicide but sufficiently low to minimize dopant deactivation within the source/drain regions.

An embodiment of the present invention is illustrated in Figs. 1A-1I. A silicon substrate is provided and can be formed from any material suitable for integrated circuit manufacture. However, in one aspect, the substrate is formed from single-crystal silicon, with a <100> crystallographic orientation and which has been slightly doped with n-type or p-type impurities. Separate MOS devices are separated on the silicon substrate using isolation structures, such as a field oxide or a shallow isolation trench (not shown).

A shallow isolation trench, for example, can be formed by etching either isotropically with wet techniques or anisotropically with dry etch techniques. An oxide is thereafter deposited within the trench. As an alternative to the shallow isolation trench, a field oxide can be formed. A field oxide is typically formed via thermal oxidation in an oxygen-steam ambient at temperatures from about 850 to 1050°C. A patterned, oxidation-resistant mask can be used to prevent oxidation of non-isolation device regions. After formation of the field oxide, the mask is removed using known techniques, for example hot phosphoric acid for a silicon nitride mask or buffered hydrofluoric acid for a pad oxide mask.

In Fig. 1A, a gate oxide 16, comprised of silicon dioxide, is formed on the top surface of the substrate 10, for example, using thermal oxidation at temperatures from about 700 to 1000°C in an oxygen-steam ambient. Although not limited in this manner, the gate oxide 16 can have a thickness

from about 3 to 20 nanometers. After deposition of the gate oxide 16, a gate electrode is formed over the gate oxide 16.

The formation of a gate electrode typically involves depositing a blanket layer of undoped polysilicon 18, for example by low pressure chemical vapor deposition (LPCVD) at temperatures from about 600 to 800°C, on the top surface of gate oxide 16. Although not limited in this manner, the polysilicon layer 18 can have a thickness from about 50 to 500 nanometers. The polysilicon layer 18 can then be implanted with nitrogen ions, as depicted by arrows 20. The implanted nitrogen ions, for example, can be used to retard the diffusion of boron atoms. The implantation of the nitrogen ions can be at a dosage from about 5×10^{14} to 5×10^{15} dopants/cm^2 and at an energy level from about 20 to 200 keV.

In Fig. 1B, the layers over the gate oxide 16 are etched to form the gate electrode. The etching of the gate typically involves forming a photoresist 22 on the polysilicon layer 18, and the photoresist 22 is selectively irradiated using a photolithographic system, such as a step and repeat optical projection system, in which ultraviolet light from a mercury-vapor lamp is projected through a first reticle and a focusing lens to obtain a first image pattern. The photoresist 22 is then developed, and the irradiated portions of the photoresist 22 are removed to provide openings in the photoresist 22. The openings expose portions of the polysilicon layer 18, which will thereby define the gate electrode.

In Fig. 1C, an etch, typically anisotropic, is applied to remove the exposed portions of the polysilicon layer 18 and the underlying portions of the gate oxide 16. After etching, the remaining portion of the polysilicon layer 18 provides a gate electrode 24 having opposing vertical sidewalls 26, 28. Although not limited in this manner, the width of the gate electrode 24 between the sidewalls 26, 28 can be from about 50 to 250 nanometers.

In Fig. 1D, the photoresist 22 is stripped, and lightly doped (LDD) source/drain extensions 30, 32 are formed by an ion implantation, as represented by arrows 34. The ion implantation may be an n-type dopant, such as arsenic or phosphorus, if an NMOSFET is desired, or a p-type dopant, such as boron, if a PMOSFET is desired. Illustrative examples of implant energies and dosages for doping respectively range from about 2 to 20 keV and from about 5×10^{14} to 3×10^{15} dopants/cm^2. The source/drain extensions 30, 32 are formed within the substrate 10 immediately adjacent to the sidewalls 26, 28 and are self-aligned with the gate electrode 24. After implantation, annealing can be conducted to activate the source/drain extensions 30, 32 and to recrystallize the extensions. Alternatively, the annealing can occur after the formation of the source/drain regions. Typically, the source/drain extensions 30, 32 extend down from the surface of the silicon substrate 10 to a depth of about 5 nanometers to 30 nanometers.

In Fig. 1E, sidewall spacers 36, 38 are formed following the implantation of the source/drain extensions 30, 32. Formation of the sidewall spacers 36, 38 involves blanket depositing a spacer material over the substrate 10. The spacer material can be silicon nitride or some other material such as plasma-enhanced oxide (PEOX) or tetraethoxysilane (TEOS) oxide. The blanket deposition is followed by an anisotropic etch, which removes the spacer material except for the sidewall spacers 26, 28 immediately adjacent to the sidewalls 26, 28 of the gate electrode 24 and over the substrate 10.

After formation of the sidewall spacers 36, 38, heavily doped (HDD) or moderately doped (MDD) source/drain regions 40, 42 are formed by a second ion implantation, as represented by arrows 44. The source/drain regions 40, 42 are formed within the substrate 10 and extend past the source/drain extensions 30, 32 immediately adjacent to the sidewall spacers 36, 38. The sidewall spacers 36, 38 act as masks, which protect portions of the source/drain extensions 30, 32 from being heavily doped. Illustrative examples of implant energies and dosages for doping respectively range from about 10 keV to 60 keV and from about 1×10^{14} to 5×10^{14} dopants/cm^2. The doping of the source/drain regions 40, 42 amorphitizes the silicon, which must then be recrystallized to activate the source/drain regions 40, 42.

In Fig. 1F, after implantation of the source/drain regions 40, 42, these regions are activated using a laser thermal annealing process. The energy from the laser, represented by arrows 70, is applied to liquefy the substrate 10 to the desired depth of source/drain regions 40, 42. An example of a laser capable of providing this energy is a spatially homogenized 308 nm XeCl pulsed laser, although the invention is not limited in this manner, and the energy and power of the laser can vary in accordance with different applications. Typically, the source/drain regions 40, 42 extend down from the surface of the silicon substrate 10 to a depth of about 40 nanometers to about 100 nanometers.

After the silicon has been melted, which is for approximately 30-100 nanoseconds, the silicon will cool rapidly, within about one microsecond, and the silicon will reform epitaxially. In so doing, damage caused by the implant process will be removed. The energy fluence of the laser at the surface determines the melt duration that occurs at the surface, and melt duration is related to maximum melt depth. The relationship between melt time and maximum melt depth depends on the temporal profile of the laser beam. Precise control of junction depth is possible due to the capability of measuring the full width height maximum (FWHM) of the laser and the surface melt duration during the process. Relatively large changes in the energy fluence are required to create small changes in the maximum melt depth. The dosage is controlled by the total melt time. The total melt time can be varied by varying the number and/or energy of the laser pulses. For example, a fluence

range of approximately 750 mJ/cm^2 to 1.3 J/cm^2 results in junction depths ranging from 20 to 150 nanometers from a 308 nm excimer laser at a 9 Hz repetition rate.

The fluence range for laser irradiation can extend all the way from about 50 mJ/cm^2 to about 1.3 J/cm^2. However, the fluence of the laser can be controlled to melt only to a depth that the silicon has been amorphitized because amorphous silicon absorbs energy at a higher rate than crystalline silicon. For example, a fluence of about 400 mJ/cm^2 can be used to melt a amorphous silicon and not melt crystalline silicon.

In Fig. 1G, nickel silicide is formed following the creation of the source/drain regions 40, 42. This process involves blanket depositing a layer of nickel 46 over the gate electrode 24 and the source/drain regions 40, 42 of the substrate 10. An illustrative example of a process capable of depositing the layer of nickel 46 is physical vapor deposition (PVD) from a nickel target. The thickness of the nickel layer 46 can be from about 8 to 20 nanometers, and most preferably from about 12 to 18 nanometers.

In Fig. 1H, the nickel layer 46 is transformed into nickel silicide 48 by a one-step thermal anneal process, which causes the silicon in the source/drain regions 40, 42 of the substrate 10 or the gate electrode 24 to react with the nickel layer 46 to form a nickel silicide layer 48. The thermal anneal is typically performed for about 30 to 60 seconds at a temperature of about 350 to 500°C in a nitrogen atmosphere. Although not limited in this manner, the thermal anneal is preferably a furnace anneal. Advantageously, because the thermal anneal is formed at a low temperature, deactivation of the dopants within the source/drain regions 40, 42 is minimized.

In Fig. 1I, the unreacted nickel layer 46 over the sidewall spacers 36, 38 is removed. For example, the unreacted nickel layer 46 can be removed using a wet chemical etch. The wet chemical etch preferably exhibits high selectivity for the unreacted metal 46 relative to the silicide 48. In current embodiments of the invention, the etch is a sulfuric peroxide mixture H_2SO_4:H_2O_2 (3:1) with deionized H_2O at a temperature of about 100°C. The removal rate of nickel at the 3:1 ratio is about 1,000 nanometers/minute.

By forming nickel silicide over the source/drain regions, which are activated by laser thermal annealing, the source/drain regions are subjected to a low post-activation temperature furnace annealing process. Advantageously, this low-temperature process reduces deactivation of dopants within the source/drain regions.

The present invention can be practiced by employing conventional materials, methodology and equipment. Accordingly, the details of such materials, equipment and methodology are not set forth herein in detail. In the previous descriptions, numerous specific details are set forth, such as specific materials, structures, chemicals, processes, etc., in order to provide a thorough

understanding of the present invention. However, it should be recognized that the present invention can be practiced without resorting to the details specifically set forth. In other instances, well-known processing structures have not been described in detail, in order not to unnecessarily obscure the present invention.

Only the preferred embodiment of the present invention and but a few examples of its versatility are shown and described in the present disclosure. It is to be understood that the present invention is capable of use in various other combinations and environments and is capable of changes or modifications within the scope of the inventive concepts as expressed herein.

CLAIMS:

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1. A method of manufacturing a semiconductor device, comprising the steps of:

forming a gate electrode 24 over a substrate 10 and a gate oxide 16 between the gate electrode 24 and the substrate 10;

implanting dopants 44 within the substrate 10 to form source/drain regions 40, 42 in the substrate 10 proximate to the gate electrode 24;

laser thermal annealing to activate the source/drain regions 40, 42; and

forming a nickel silicide layer 48 disposed on the source/drain regions 40, 42, wherein said nickel silicide forming step includes a step of annealing at temperatures from 350 to 500 °C.

2. The method of manufacturing a semiconductor device according to claim 1, wherein said nickel silicide forming step includes a step of depositing nickel 46 over the source/drain regions 40, 42.

3. The method of manufacturing a semiconductor device according to claim 1, wherein said nickel silicide forming step includes a step of depositing about 8 to 20 nanometers of nickel 46 over the source/drain regions 40, 42.

4. The method of manufacturing a semiconductor device according to any one of claims 1 to 3, further comprising steps of forming source/drain extensions 30, 32 in the substrate 10 adjacent to the gate electrode 24 and forming sidewall spacers 36, 38 adjacent to the gate electrode 24.

5. The method of manufacturing a semiconductor device according to claim 4, wherein the source/drain extensions 30, 32 have a depth of about 5 to 30 nanometers.

6. The method of manufacturing a semiconductor device according to any one of claims 1 to 5, wherein the source/drain regions 40, 42 have a depth of about 40 to 100 nanometers.

7. The method of manufacturing a semiconductor device according to any one of claims 1 to 6, wherein said step of forming source/drain regions 40, 42 amorphitizes a region in the substrate 10.

8. The method of manufacturing a semiconductor device according to claim 7, wherein said step of activating the source/drain regions 40, 42 by laser thermal annealing melts the amorphitized region and not crystalline silicon.

9. A method of manufacturing a semiconductor device according to any one of claims 1 to 8, wherein the semiconductor is a MOSFET device.

10. The method of manufacturing a semiconductor device according to claim 1, wherein said step of forming a nickel silicide layer 48 disposed on the source/drain regions 40, 42 is after said step of laser thermal annealing of the source/drain regions 40, 42.

11. The method of manufacturing a semiconductor device according to claim 1, wherein said nickel silicide forming step includes a step of annealing at temperatures below a temperature at which deactivation of the dopants in the source/drain regions 40, 42 occur.

12. A method of manufacturing a MOSFET semiconductor device, comprising the steps of:

forming a gate electrode 24 over a substrate 10 and a gate oxide 16 between the gate electrode 24 and the substrate 10;

forming source/drain extensions 30, 32 in the substrate 10 adjacent to the gate electrode at a depth of about 5 to 30 nanometers;

forming first and second sidewall spacers 36, 38 adjacent to the gate electrode 24;

implanting dopants 44 within the substrate 10 to form source/drain regions 40, 42 in the substrate 10 adjacent to the sidewall spacers 36, 38 at a depth of about 40 to 100 nanometers;

laser thermal annealing to activate the source/drain regions 40, 42;

depositing a layer of nickel 46 over the source/drain regions 40, 42; and

annealing at temperatures from about 350 to 500 °C form a nickel silicide layer 46 disposed on the source/drain regions 40, 42.