



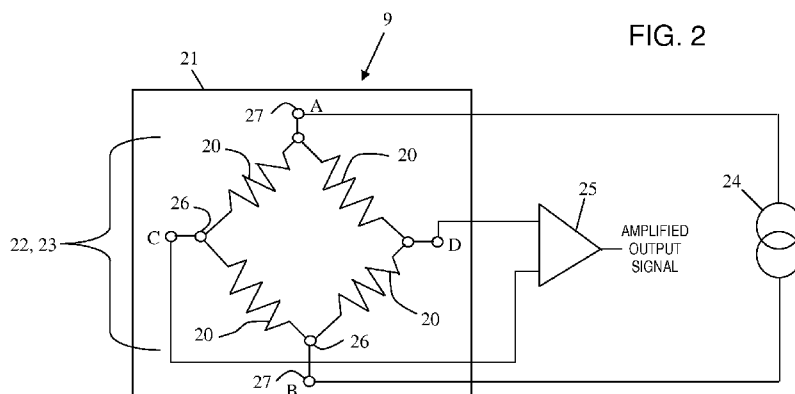
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(54) Title: HIGH TEMPERATURE PIEZORESISTIVE STRAIN GAUGES MADE OF SILICON-ON-INSULATOR



(57) Abstract: Disclosed is an apparatus for measuring a parameter in a borehole penetrating the earth. The apparatus includes a sensor configured to be disposed in the borehole and having a piezo-resistor fabricated from a semiconductor on an insulator wherein a portion of the semiconductor is etched to the insulator to form the piezo-resistor, the piezo-resistor being responsive to the parameter.

HIGH TEMPERATURE PIEZORESISTIVE STRAIN GAUGES MADE OF SILICON-ON-INSULATOR

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Application No. 61/453,632, filed on March 17, 2012, which is incorporated herein by reference in its entirety.

BACKGROUND

1. Field of the Invention

[0002] The invention disclosed herein relates to measuring parameters in a downhole environment and, in particular, to measuring the parameters using a resistive bridge.

2. Description of the Related Art

[0003] Boreholes are drilled deep into the earth for many applications such as carbon sequestration, geothermal production, and hydrocarbon exploration and production. Many different types of tools and instruments may be disposed in the boreholes to perform various tasks. These tools and instruments generally include one or more sensors used to measure parameters such as pressure or strain. Typically, very high temperatures up to 200 °C or even more are encountered by the tools and instruments and, thus, the sensors when they are disposed deep into the earth.

[0004] Piezoresistive bridges are widely used in sensors for highly sensitive measurements of mechanical stress in very small sensors. However, their use at high temperatures is limited to less than about 125 °C due to leakage currents. Compensating circuits to compensate for the leakage currents add complexity to the sensors. In addition, the compensating circuits cannot fully compensate for the strong temperature dependence of the measured signal resulting in inaccurate measurements. It would be well received in the drilling industry if sensors could be improved to operate accurately at high downhole temperatures.

BRIEF SUMMARY

[0005] Disclosed is an apparatus for measuring a parameter in a borehole penetrating the earth. The apparatus includes a sensor configured to be disposed in the borehole and having a piezo-resistor fabricated from a semiconductor on an insulator wherein a portion of

the semiconductor is etched to the insulator to form the piezo-resistor, the piezo-resistor being responsive to the parameter.

[0006] Also disclosed is an apparatus for measuring a parameter in a borehole penetrating the earth. The apparatus includes: a carrier configured to be conveyed through the borehole; and a sensor disposed at the carrier and having a piezo-resistor fabricated from a semiconductor on an insulator wherein a portion of the semiconductor is etched to the insulator to form the piezo-resistor, the piezo-resistor being responsive to the downhole parameter.

[0007] Further disclosed is a method for measuring a parameter in a borehole penetrating the earth. The method includes: disposing a sensor into the borehole, the sensor having a piezo-resistor fabricated from a semiconductor on an insulator wherein a portion of the semiconductor is etched to the insulator to form the piezo-resistor, the piezo-resistor being responsive to the parameter; and measuring the parameter using the sensor.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] The following descriptions should not be considered limiting in any way. With reference to the accompanying drawings, like elements are numbered alike:

[0009] FIG. 1 illustrates an exemplary embodiment of a downhole tool having a sensor disposed in a borehole penetrating the earth;

[0010] FIG. 2 depicts aspects of the sensor having a piezoresistive bridge;

[0011] FIG. 3 depicts aspects of silicon-on-insulator construction;

[0012] FIG. 4 presents one example of a method for estimating a downhole parameter; and

[0013] FIGS. 5A-5H, collectively referred to as FIG. 5, depict aspects of fabricating the sensor using a double-layer silicon on insulator material.

DETAILED DESCRIPTION

[0014] A detailed description of one or more embodiments of the disclosed apparatus and method presented herein by way of exemplification and not limitation with reference to the Figures.

[0015] FIG. 1 illustrates an exemplary embodiment of a downhole tool 10 disposed in a borehole 2 penetrating the earth 3, which includes an earth formation 4. The earth formation 4 represents any subsurface materials of interest. The downhole tool 10 includes a

sensor 9 configured to perform a measurement of a parameter in the borehole 2. Non-limiting embodiments of the parameter include stress, strain, pressure, force, acceleration, contact, tilt, and magnetic fluctuations. In one embodiment of FIG. 1, the downhole tool 10 is configured to perform a measurement of a property of the formation 4 in conjunction with an instrument 11 and the sensor 9. For example, in one embodiment, the instrument 11 is a formation tester configured to extract a formation fluid from the formation 4. The sensor 9 can be used to measure the pressure at which the formation fluid begins to flow into the downhole tool 10 to estimate the formation fluid pressure.

[0016] Still referring to FIG. 1, the downhole tool 10 is conveyed through the borehole 2 by a carrier 5. In FIG. 1, a measurement-while-drilling (MWD) embodiment is depicted in which the carrier 5 is a drill string 6. In one or more embodiments, the downhole tool 10 is disposed in a drill collar surrounding the drill string 6. At the distal end of the drill string 6 is a drill bit 7. A drilling rig 8 is configured to rotate the drill string 5 and the drill bit 7 in order to drill the borehole 2. In alternative embodiments, the carrier 5 can be a wireline used for wireline logging applications in existing boreholes.

[0017] In one embodiment, a surface computer processing system 13 is used to record, process, or display measurements performed by the downhole tool 10 and/or the sensor 9. In order to operate the downhole tool 10, process and record data, and/or provide a communications interface with the surface computer processing system 13, the downhole tool 10 includes downhole electronics 12.

[0018] Reference may now be had to FIG. 2 depicting aspects of the sensor 9. The sensor 9 includes one or more piezo-resistors 20, which are built using semiconductor fabrication technology. Resistance changes in the piezo-resistors 20 are due to a piezoresistive effect. In one embodiment, the piezo-resistors 20 are built into a semiconductor 21 such as a monocrystalline semiconductor having a crystal lattice. Doping of the semiconductor 21 is used to define the conductivity characteristics of the semiconductor 21 and, thus, the piezo-resistors 20. Conductivity in the doped semiconductor 21 is influenced by a deformation of the crystal lattice such as by stretching or compression of the crystal lattice. Extremely small mechanical deformations of the crystal lattice can be measured to provide the sensor 9 with high sensitivity resulting in measurements having very high accuracy. In addition, the piezo-resistors 20 provide good linearity without signal hysteresis up to the point where the piezo-resistors 20 will destruct.

[0019] Still referring to FIG. 2, the piezo-resistors 20 are coupled to form a network 22. In one embodiment, the network 22 forms a Wheatstone bridge 23 as shown in FIG. 2. The network 22 also includes interconnects 26 between the piezo-resistors 20 and terminals 27 providing connections to external components. A constant current source 24 supplies a constant current input electrical signal to terminals A and B of the bridge 23. An output signal from the bridge 23 at terminals C and D is measured by an amplifier 25. The output signal will change in response to a change in the parameter being measured by the sensor 9. Hence, by measuring a change in the output signal, a change in the parameter can be measured. Different networks 22 and piezoresistive bridges can be used depending on the application of the sensor 9. One of skill in the art will understand the operation of Wheatstone bridges and bridges in general.

[0020] It can be appreciated that the network 22 may form other types of bridges that use one or more of the piezo-resistors 20 as components. Other types of bridges include a Kelvin bridge and a Wein bridge. In one embodiment, the Wein bridge is used as an oscillator. As the values of the piezo-resistors 20 change from deformation of the crystal lattice in response to the measured parameter, the frequency of the oscillator will change. By measuring a change in the output frequency of the oscillator, a change in the parameter can be measured.

[0021] Reference may now be had to FIG. 3 depicting aspects of the semiconductor 21. The semiconductor 21 is made as a layer of a silicon-on-insulator (SOI) wafer or substrate 30. The SOI wafer 30 includes a layer of the semiconductor 21, an insulator layer 31, and another semiconductor layer 32. Non-limiting embodiments of materials used to form the insulator layer 31 include silicon dioxide and sapphire. The other semiconductor layer 32 can be the same material as the semiconductor 21 such as monocrystalline silicon for example. The piezo-resistors 20, the interconnects 26, and the terminals 27 are formed by removing material in the semiconductor 21 layer down to the insulator layer 31. Removing material from the layer of the semiconductor 21 down to the insulator layer 31 eliminates leakage currents or limits leakage currents to very low acceptable levels between the piezo-resistors 20, interconnects 26, terminals 27, or other electrical components formed in the semiconductor 21 layer. By eliminating the leakage currents or keeping them very low, the sensor 9 can operate and maintain accuracy, precision and linearity in high downhole temperatures up to and exceeding 300 °C.

[0022] It can be appreciated that the semiconductor 21 can be doped in n-type or p-type doping materials with a concentration up to the degeneration region (i.e., where a semiconductor stops acting as a semiconductor) of the semiconductor 21. With a high concentration of the n-type or p-type doping materials, a very low temperature coefficient for both the resistivity and the piezoresistive coefficient of the piezo-resistors 20 can be achieved.

[0023] It can be appreciated that the material in the layer of the semiconductor 21 can be removed down to the insulator layer 31 by known semiconductor circuit fabrication processes such as etching by chemicals or physical.

[0024] It can be appreciated that the sensor 9 can be configured as a Hall sensor (i.e., a sensor that senses a changing or fluctuating magnetic field). In a Hall sensor embodiment, the sensor 9 can have magnetic particles embedded in the monocrystalline structure of the piezo-resistors 20. The magnetic particles will interact with the changing magnetic field in to mechanically deform the crystal lattice, and, thus change the conductivity of the piezo-resistors 20.

[0025] It can be appreciated that the sensor 9 can be configured as a tilt sensor (i.e., a sensor that can measure a deviation in orientation with respect to earth gravity). In a tilt sensor embodiment, the sensor 9 can include a proof mass coupled to one or more of the piezo-resistors 20. As the sensor 9 tilts, the direction of gravity acting on the proof mass will change and mechanically deform the crystal lattice, and, thus change the conductivity of the one or more piezo-resistors 20.

[0026] It can be appreciated that the sensor 9 can be configured to measure pressure. In a pressure sensing embodiment, the sensor 9 can include a diaphragm in communication with the pressure and coupled to one or more of the piezo-resistors 20. The pressure acting on the diaphragm will mechanically deform the crystal lattice, and, thus change the conductivity of the piezo-resistors 20.

[0027] It can be appreciated that the sensor 9 can be configured to be a contact sensor (i.e., a sensor that can sense contact with an object). In a contact sensor embodiment, the sensor 9 can include a contact element coupled to one or more of the piezo-resistors 20 and configured to contact the object. Upon contacting the object, the contact element transfers a contact force to the crystal lattice to mechanically deform the crystal lattice, and, thus change the conductivity of the piezo-resistors 20.

[0028] It can be appreciated that the sensor 9 can be configured to measure vibrations. In a vibration sensor embodiment, the sensor 9 can include a proof mass coupled to one or more of the piezo-resistors 20. Due to vibrations (e.g., caused by interactions between chisel and formation), forces acting on the proof mass will change and mechanically deform the crystal lattice, and, thus change the conductivity of the one or more piezo-resistors 20.

[0029] FIG. 4 presents one example of a method 40 for measuring a downhole parameter. The method 40 calls for (step 41) disposing a sensor in a borehole penetrating subsurface materials. The sensor includes one or more piezo-resistors fabricated from a semiconductor on an insulator by removing or etching semiconductor material down to the insulator. At least one of the one or more piezo-resistors is configured to measure the downhole parameter and output a signal corresponding to the measured downhole parameter. In one embodiment, a plurality of piezo-resistors forms a network or bridge that outputs a signal corresponding to the measured downhole parameter. Further, the method 40 calls for (step 42) measuring the downhole parameter using the sensor.

[0030] In an alternative embodiment, the SOI wafer 30 may be a double-layer silicon on insulator material 50 as illustrated in FIG. 5. The double-layer silicon on insulator (DL-SOI) material 50 improves the precision of manufacturing in order to improve the accuracy and precision for the sensor 9 by better defining the resonance frequency. With the DL-SOI material 50, the etching of silicon may stop at the oxide layer when it is reached by dry etching. In one or more embodiments, the DL-SOI material 50 is used to fabricate the sensor 9 having a mass 51 and a spring 52 as illustrated in FIG. 5C. Non-limiting examples of these types of sensors include the tilt sensor, the vibration sensor, and an accelerometer.

[0031] FIGS. 5A-5H depict aspects of fabrication of the sensor 9 having the mass 51 and the spring 52 from the DL-SOI wafer 50. FIG. 5A illustrates the DL-SOI wafer 50 before semiconductor fabrication operations are applied to it. FIG. 5B illustrates the wafer 50 having reduced contact resistance (p++), metallization of measuring bridge (front side), metallization of die attach by Ag-Sintering (back side), and Cr metallization for protection while etching. FIG. 5C illustrates results of etching of the front side, realization of measuring bridge by etching of the resistors, and modeling of the mass 50 and the spring 51. FIG. 5D illustrates results of oxid etching of the front side. FIG. 5E illustrates results of etching of the front side to create the mass 51. FIG. 5F illustrates results of etching the back side of the wafer 50 to define the size of the mass 51. FIG. 5G illustrates results of etching without a

mask, defining the size of the spring 52, and evacuation of the mass 51. FIG. 5H illustrates of further oxid etching and Cr-etching for die attach.

[0032] In support of the teachings herein, various analysis components may be used, including a digital and/or an analog system. For example, the downhole electronics 12, the surface computer processing system 13, the constant current source 24, or the amplifier 25 may include the digital and/or analog system. The system may have components such as a processor, storage media, memory, input, output, communications link (wired, wireless, pulsed mud, optical or other), user interfaces, software programs, signal processors (digital or analog) and other such components (such as resistors, capacitors, inductors and others) to provide for operation and analyses of the apparatus and methods disclosed herein in any of several manners well-appreciated in the art. It is considered that these teachings may be, but need not be, implemented in conjunction with a set of computer executable instructions stored on a computer readable medium, including memory (ROMs, RAMs), optical (CD-ROMs), or magnetic (disks, hard drives), or any other type that when executed causes a computer to implement the method of the present invention. These instructions may provide for equipment operation, control, data collection and analysis and other functions deemed relevant by a system designer, owner, user or other such personnel, in addition to the functions described in this disclosure.

[0033] Further, various other components may be included and called upon for providing for aspects of the teachings herein. For example, a power supply (e.g., at least one of a generator, a remote supply and a battery), magnet, electromagnet, sensor, electrode, transmitter, receiver, transceiver, antenna, controller, optical unit, electrical unit or electromechanical unit may be included in support of the various aspects discussed herein or in support of other functions beyond this disclosure.

[0034] The term “carrier” as used herein means any device, device component, combination of devices, media and/or member that may be used to convey, house, support or otherwise facilitate the use of another device, device component, combination of devices, media and/or member. Other exemplary non-limiting carriers include drill strings of the coiled tube type, of the jointed pipe type and any combination or portion thereof. Other carrier examples include casing pipes, wirelines, wireline sondes, slickline sondes, drop shots, bottom-hole-assemblies, drill string inserts, modules, internal housings and substrate portions thereof.

[0035] Elements of the embodiments have been introduced with either the articles “a” or “an.” The articles are intended to mean that there are one or more of the elements. The terms “including” and “having” are intended to be inclusive such that there may be additional elements other than the elements listed. The conjunction “or” when used with a list of at least two terms is intended to mean any term or combination of terms. The terms “first” and “second” are used to distinguish elements and are not used to denote a particular order. The term “couple” relates to two devices being coupled either directly or indirectly via an intermediate device.

[0036] It will be recognized that the various components or technologies may provide certain necessary or beneficial functionality or features. Accordingly, these functions and features as may be needed in support of the appended claims and variations thereof, are recognized as being inherently included as a part of the teachings herein and a part of the invention disclosed.

[0037] While the invention has been described with reference to exemplary embodiments, it will be understood that various changes may be made and equivalents may be substituted for elements thereof without departing from the scope of the invention. In addition, many modifications will be appreciated to adapt a particular instrument, situation or material to the teachings of the invention without departing from the essential scope thereof. Therefore, it is intended that the invention not be limited to the particular embodiment disclosed as the best mode contemplated for carrying out this invention, but that the invention will include all embodiments falling within the scope of the appended claims.

CLAIMS

What is claimed is:

1. An apparatus for measuring a parameter in a borehole penetrating the earth, the apparatus comprising:
a sensor configured to be disposed in the borehole and having a piezo-resistor fabricated from a semiconductor on an insulator wherein a portion of the semiconductor is etched to the insulator to form the piezo-resistor, the piezo-resistor being responsive to the parameter.
2. The apparatus according to claim 1, wherein the piezo-resistor comprises a plurality of piezo-resistors.
3. The apparatus according to claim 2, wherein the plurality of piezo-resistors comprises a network.
4. The apparatus according to claim 3, wherein the network comprises an electrical bridge.
5. The apparatus according to claim 4, wherein the electrical bridge comprises a Wheatstone bridge.
6. The apparatus according to claim 1, wherein the semiconductor is doped with n-type or p-type doping material up to a degeneration region of the semiconductor.
7. The apparatus according to claim 1, wherein the semiconductor comprises silicon and the insulator comprises silicon dioxide.
8. The apparatus according to claim 1, further comprising an electrical signal source coupled to the piezo-resistor to energize the piezo-resistor.
9. The apparatus according to claim 1, further comprising an amplifier coupled to the piezo-resistor and configured to amplify an output signal corresponding to the measured parameter.
10. The apparatus according to claim 1, wherein the parameter is at least one of acceleration, force, tilt, contact, pressure, strain, stress, and magnetic field fluctuations.
11. The apparatus according to claim 10, wherein the sensor is configured as a Hall sensor.
12. The apparatus according to claim 10, wherein the parameter is related to a property of an earth formation penetrated by the borehole.
13. The apparatus according to claim 1, wherein the semiconductor is on a first insulator separated from a second insulator.

14. An apparatus for measuring a parameter in a borehole penetrating the earth, the apparatus comprising:

a carrier configured to be conveyed through the borehole; and

a sensor disposed at the carrier and having a piezo-resistor fabricated from a semiconductor on an insulator wherein a portion of the semiconductor is etched to the insulator to form the piezo-resistor, the piezo-resistor being responsive to the downhole parameter.

15. The apparatus according to claim 14, wherein the carrier is a drill string.

16. A method for measuring a parameter in a borehole penetrating the earth, the method comprising:

disposing a sensor into the borehole, the sensor having a piezo-resistor fabricated from a semiconductor on an insulator wherein a portion of the semiconductor is etched to the insulator to form the piezo-resistor, the piezo-resistor being responsive to the parameter; and measuring the parameter using the sensor.

17. The method according to claim 16, further comprising energizing the piezo-resistor with an input electrical signal.

18. The method according to claim 17, further comprising receiving an output electrical signal due to the energizing wherein the output electrical signal relates to the measured parameter.

19. The method according to claim 16, further comprising at least one of recording the measured parameter, transmitting the measured parameter to downhole electronics, or transmitting the measured parameter to a processing system disposed at the surface of the earth.

20. The method according to claim 15, wherein the parameter is at least one of acceleration, force, tilt, contact, pressure, strain, stress, and magnetic field fluctuations.

21. The method according to claim 19, wherein the parameter is related to a property of an earth formation penetrated by the borehole.

22. The method according to claim 16, wherein the semiconductor is on a first insulator separated from a second insulator.

FIG. 1

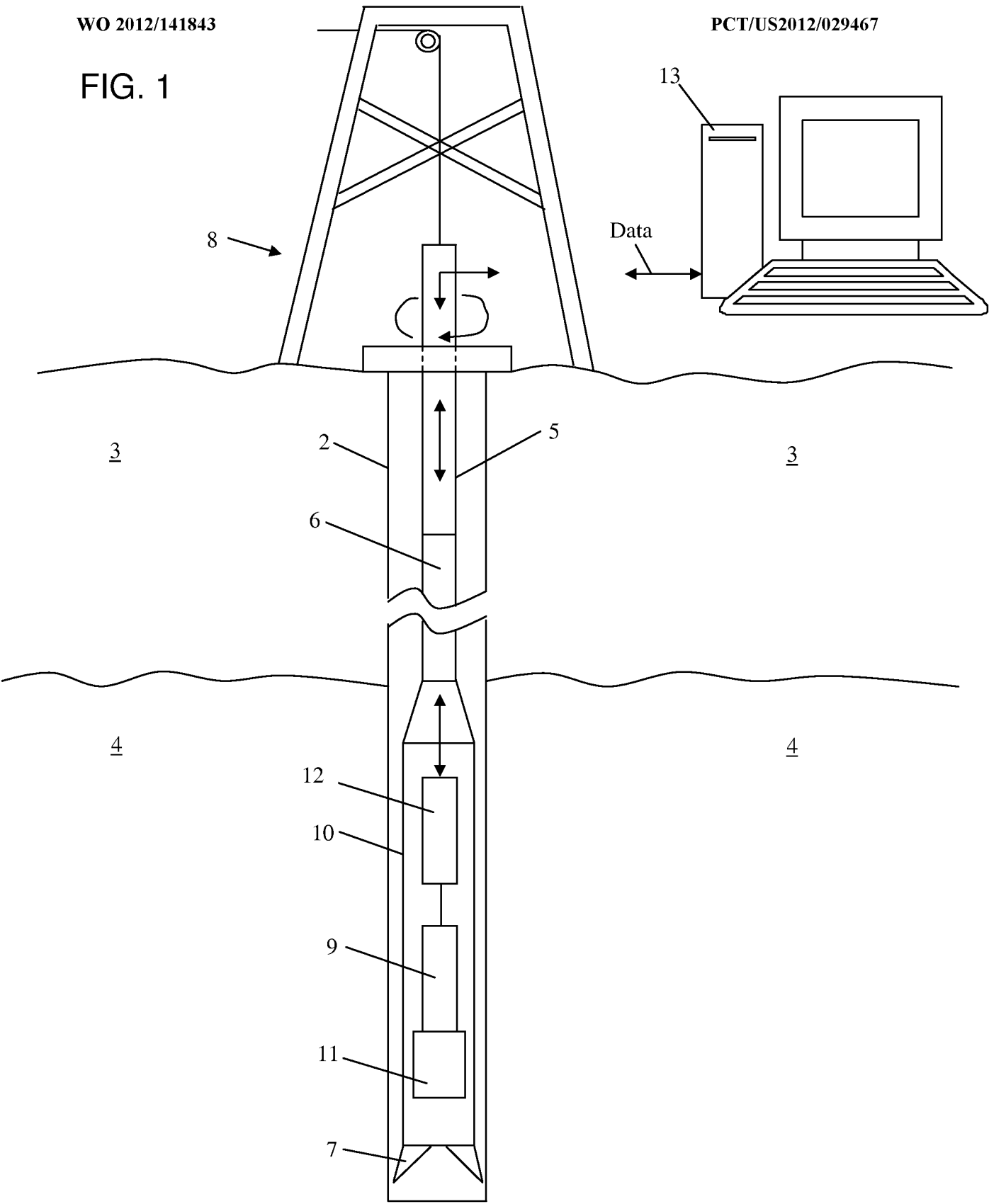


FIG. 2

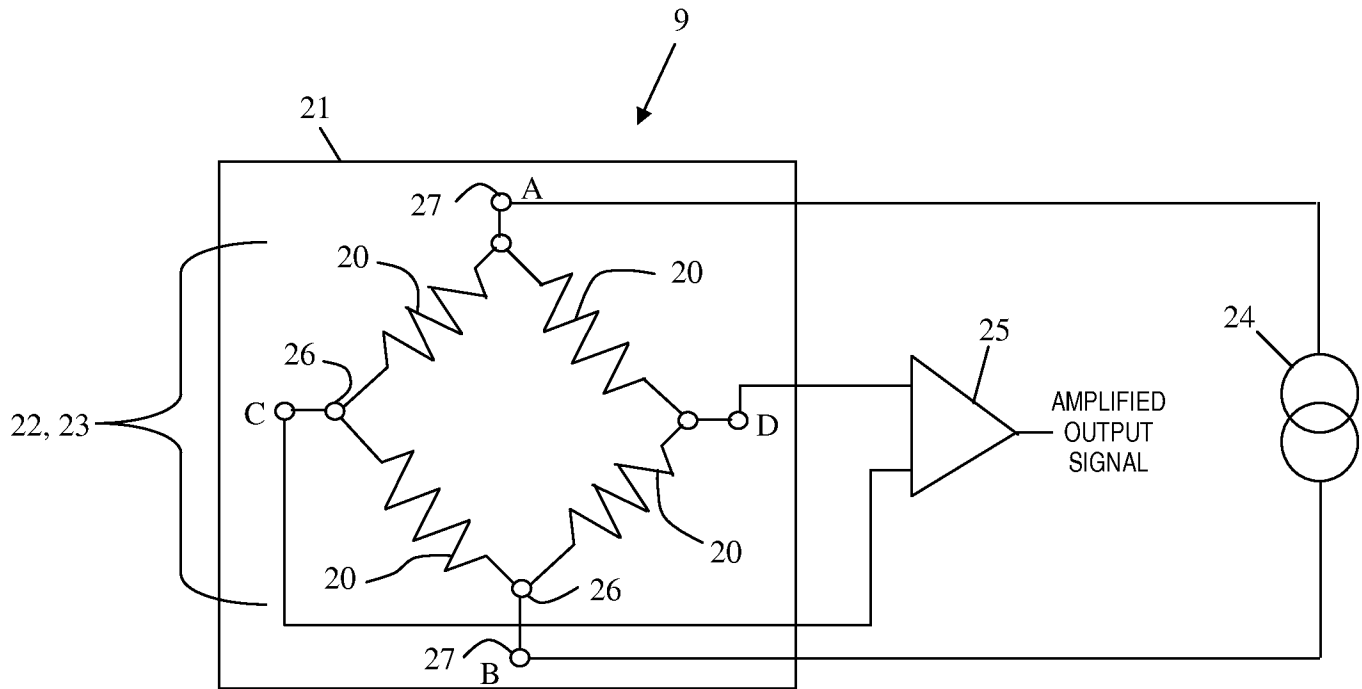
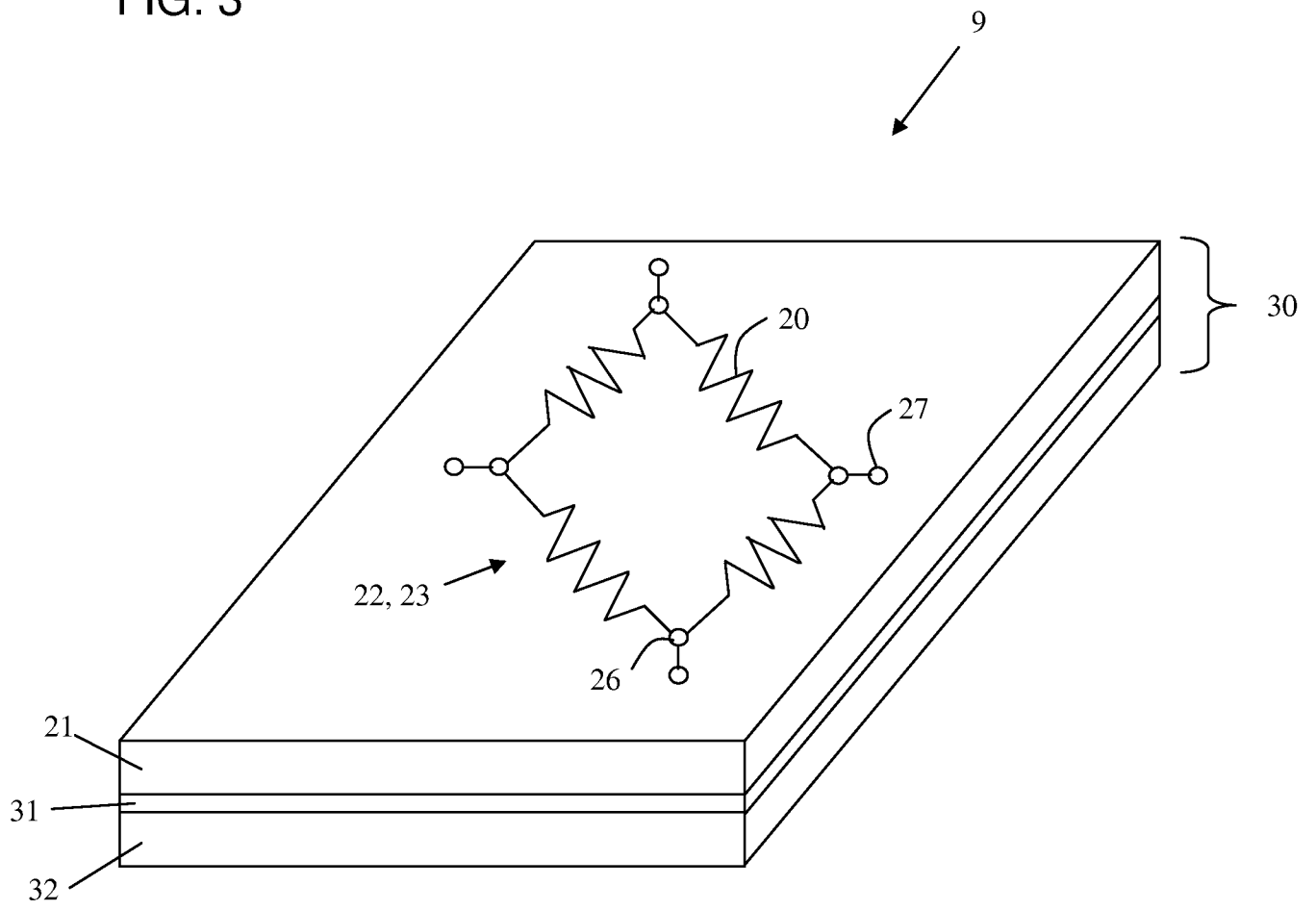


FIG. 3



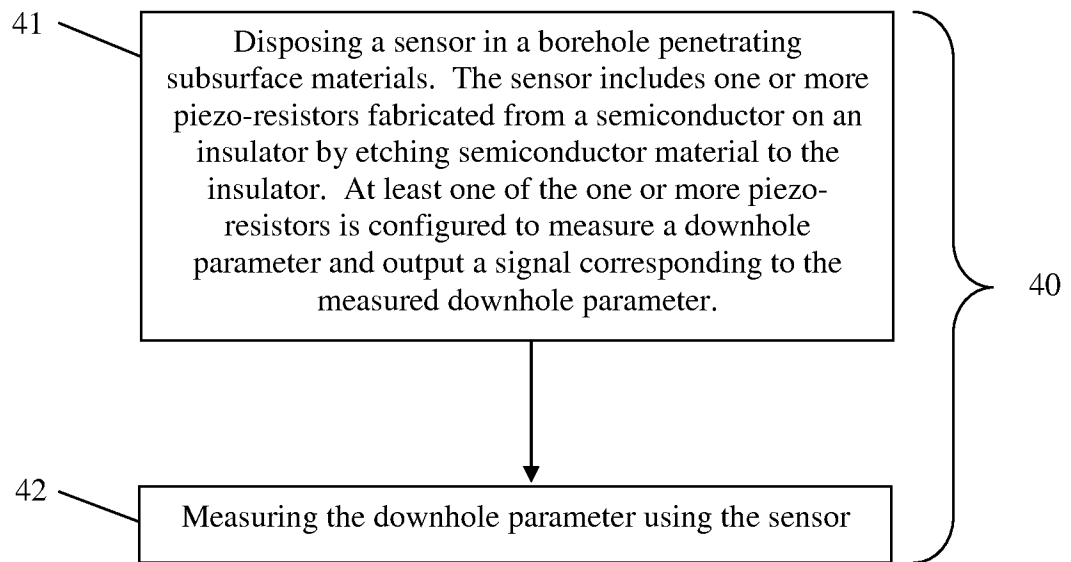


FIG. 4

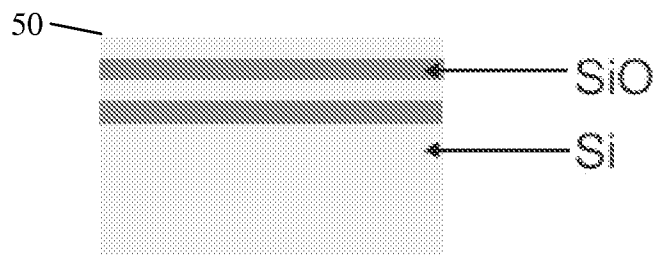


FIG. 5A

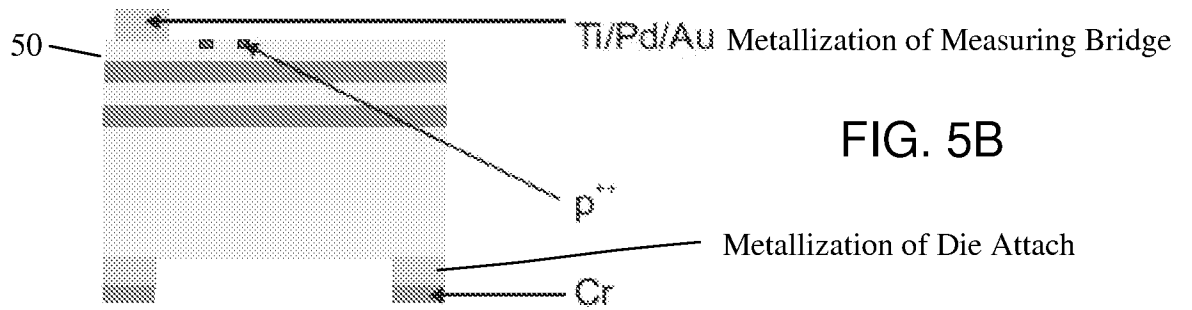


FIG. 5B

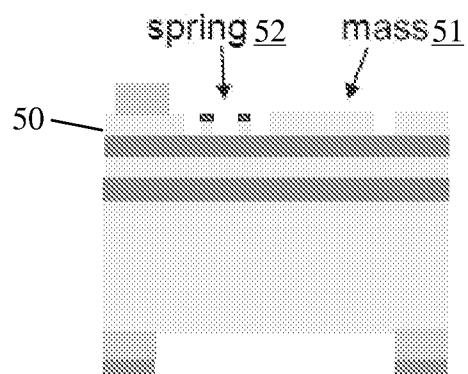


FIG. 5C

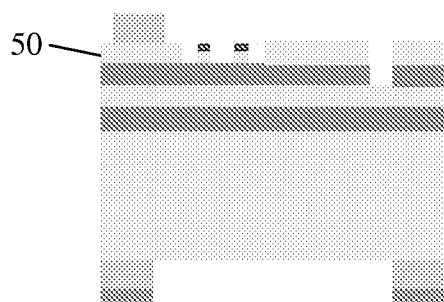


FIG. 5D

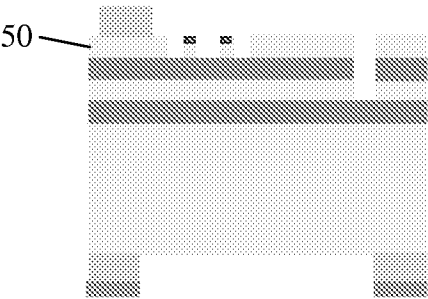


FIG. 5E

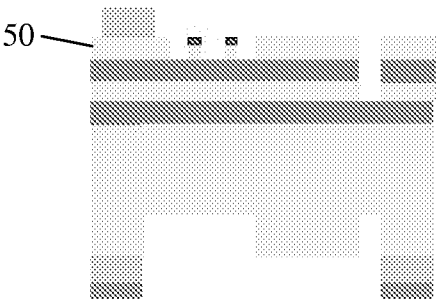


FIG. 5F

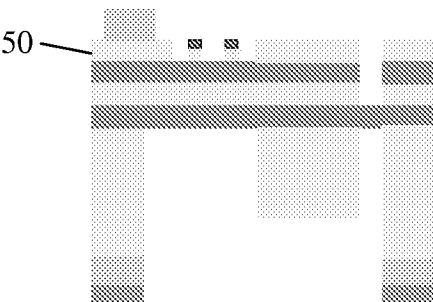


FIG. 5G

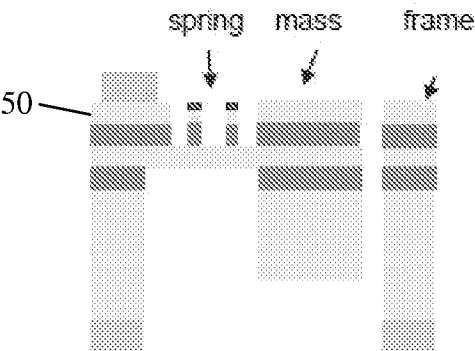


FIG. 5H