(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
13 October 2011 (13.10.2011)

PCT

(10) International Publication Number
WO 2011/127114 A2

(51) International Patent Classification: Not classified

(21) International Application Number:
PCT/US2011/031332

(22) International Filing Date:
6 April 2011 (06.04.2011)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
61/321,554 7 April 2010 (07.04.2010) US
13/079,948 5 April 2011 (05.04.2011) US

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(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

[Continued on next page]

(54) Title: OIL-BASED MUD IMAGER WITH A LINE SOURCE

(57) Abstract: A resistivity imaging device uses a line source in conjunction with an array of measure electrodes to reduce sensitivity to tool standoff when use in a borehole with oil-based mud.

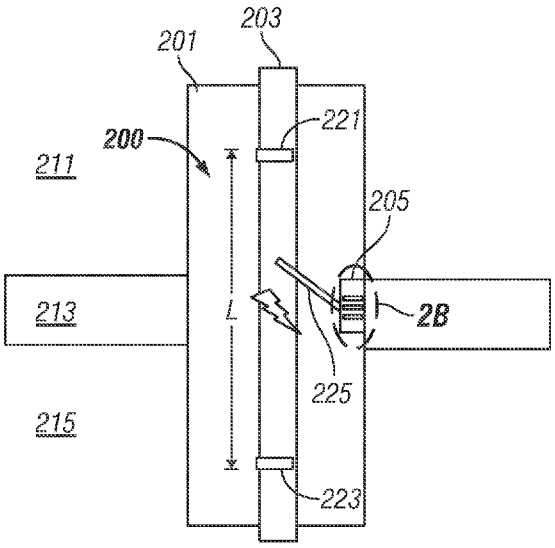


FIG. 2A

WO 2011/127114 A2

— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

Published:

— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

OIL-BASED MUD IMAGER WITH A LINE SOURCE

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BACKGROUND OF THE DISCLOSURE

Field of the Disclosure

[0001] The disclosed disclosure is related to downhole well investigation methods and, in particular, to measuring a resistivity property of an earth formation from a borehole containing non-conductive mud.

Description of the Related Art

[0002] A big challenge in oil-based mud imaging tools using electrodes is to reduce or correct the standoff effects. This is due to the fact that changes in tool standoff from the borehole wall produce variations in the current in the electrodes that mask any current variation in the formation being measured. When the standoff is large, current flow between the electrodes also become important. Capacitive coupling has been used for conveying currents into the formation, but at the high frequencies needed for capacitive coupling, the capacitance between the electrodes becomes a serious problem.

[0003] The present disclosure addresses this problem using a line source for conveying current into the formation.

SUMMARY OF THE DISCLOSURE

[0004] One embodiment of the present disclosure is an apparatus configured to evaluate an earth formation. The apparatus includes: a carrier including a line source of electric current configured to be conveyed in a borehole; and at least one pair of electrodes proximate to a wall of the borehole, a difference in potential between a first one of the at least one pair of electrodes and a second one of the at least one pair of electrodes being indicative of a resistivity property of the earth formation

[0005] Another embodiment of the disclosure is a method of evaluating an earth formation. The method includes: activating a line source of electric current conveyed on a carrier in a borehole; providing a first signal from a first one of at least one pair of electrodes proximate to a wall of the borehole indicative of a potential of the first one of the electrodes and a second signal from a second one of the at least one pair of electrodes indicative of a potential of the second one of the electrodes; and using a processor for estimating a resistivity property of the earth formation using the first signal and the second signal.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] For detailed understanding of the present disclosure, references should be made to the following detailed description of an exemplary embodiment, taken in conjunction with the accompanying drawings, in which like elements have been given like numerals, wherein:

FIG. 1 shows an exemplary imaging tool suitable for use with this disclosure suspended in a borehole;

FIG. 2a shows a detail of one embodiment of the present imaging tool suspended in a borehole;

FIG. 2b shows a detail of a pad of the imaging tool;

FIG. 3a shows an illustration of one embodiment of the present imaging tool suspended in a borehole with the line source on a pad;

FIG. 3b shows a detail of a pad of the imaging tool of Fig. 3a;

FIG. 3c shows the configuration of an alternate embodiment of the disclosure;

FIGS. 4a-d shows different configurations of a line source including toroidal coils on a conductive member;

FIGS. 5a-5b show an embodiment of the disclosure wherein only vertical measurements are made; and

FIG. 6 shows a modeled response of the tool configuration of **Fig. 5** as a function of bed thickness and tool standoff.

DETAILED DESCRIPTION OF THE DISCLOSURE

[0007] **FIG. 1** shows an imaging tool **10** suspended in a borehole **12**, that penetrates earth formations such as **13**, from a suitable cable **14** that passes over a sheave **16** mounted on drilling rig **18**. By industry standard, the cable **14** includes a stress member and seven conductors for transmitting commands to the tool and for receiving data back from the tool as well as power for the tool. The tool **10** is raised and lowered by draw works **20**. Electronic module **22**, on the surface **23**, transmits the required operating commands downhole and in return, receives data back which may be recorded on an archival storage medium of any desired type for concurrent or later processing. The data may be transmitted in analog or digital form. Data processors

such as a suitable computer **24**, may be provided for performing data analysis in the field in real time or the recorded data may be sent to a processing center or both for post processing of the data. Some of the data processing may also be done by a downhole computer. Novel aspects of the imaging tool of the present disclosure are discussed next.

[0008] FIG. 2a shows an exemplary imaging tool **200** of the present disclosure disposed in a borehole **201.** Three intervals of the formation **211, 213** and **215** are shown. The logging tool **200** includes a conductive member **203** that is shown with two toroidal coils **221, 223** spaced a distance '**L**' apart. For an MWD implementation, the conductive member may be a drill pipe while for a wireline implementation, the conductive member may be a metal rod inside a non-conducting mandrel. For the purposes of the present disclosure, the logging tool **200** may be referred to as a carrier. The term "carrier" is also intended to include a bottomhole assembly conveyed on a drilling tubular for MWD implementation.

[0009] A sensor pad **207** shown in **Fig. 2b** is positioned in proximity to a wall of the borehole. For the present disclosure, the term "proximate" includes "in contact with" as well as "close to." The term "close to" in the context of the present disclosure is intended to mean that the sensor pad **207** is close enough to make measurements of formation resistivity as discussed further below. The sensor pad may be referred to as a contact member and includes an array of electrodes **209**. The array of electrodes may be a two-dimensional array as shown in **Fig. 2b.** The sensor pad is coupled to the carrier by a coupling member such as extension rod **225.**

[0010] Of interest are potential differences indicated by ΔV_1, ΔV_2, ΔV_3 and ΔV_4 that may be measured between adjacent electrodes in the 2-d array of electrodes responsive to activation of the coil(s) **221, 223.** Those knowledgeable in the art and having benefit of the present disclosure would recognize that the arrangement of the coil(s) **221, 223** and the conductive member **203** forms a line source of current. The combination of the line source and a pair of electrodes may be viewed as a three terminal device. It should be noted that the current distribution of the line source as illustrated is not the same as that of an axially oriented transmitter, i.e., a dipole antenna.

[0011] From the measured potential differences, the following quantities indicative of the resistivity property of the earth formation may be calculated:

$$E = \sqrt{\left(\frac{\Delta V_1 + \Delta V_2}{2}\right)^2 + \left(\frac{\Delta V_3 + \Delta V_4}{2}\right)^2},$$
$$\Delta E = \sqrt{(\Delta V_1 - \Delta V_2)^2 + (\Delta V_3 - \Delta V_4)^2} \quad \textit{and} \qquad (1).$$
$$\Delta E / E.$$

[0012] **Figs. 3a-3c** shows an alternate embodiment of the disclosure in which the line source is formed by a longitudinal metal rod with at least one toroidal coil **301** on the back of the sensor pad. The same quantities given by **eqn. (1)** can be measured. Due to the shorter length of the metal rod **301** compared to the rod **203,** the standoff effects are larger, but the azimuthal resolution is improved. In an optional embodiment, and additional line source (transverse) **301′** may be provided. When measurements are

made responsive to activation of the longitudinal line source and the transverse source, it is possible to accurately determine the orientation of dipping beds and anisotropy. This is discussed in US 7,365,545 to *Itskovich* et al., having the same assignee as the present disclosure and the contents of which are incorporated herein by reference.

[0013] Turning now to **Figs 4a-4d**, different line sources comprising a conductive member **203** and one or more toroidal coils **401** are illustrated. The more the number of toroidal coils, the better will be the line source.

[0014] **FIGS. 5a-5b** show an embodiment of the disclosure wherein only vertical measurements are made. As shown in **Fig. 5b**, two rows of electrodes are used. Consequently, only first differences in the vertical direction, denoted by V_z are made in contrast to the plurality of differences possible with the electrode configuration of **Figs. 2** and **3.**

[0015] Modeling results with two receiver electrodes are used to obtain voltage difference and shown in **Fig. 6.** The spacing between two toroidal coils is 4m. The pad and electrodes are expanded circumferentially to conform to a 2.5D forward modeling engine. A multiple layer model with different layer thickness from 0.5" to 4" (1.25cm to 10 cm) is used to check the vertical resolution of the design. Also, different standoffs ranging from 0.125 in to 0.5 in. (3.125mm to 12.7 mm) is used to check the standoff effects for the design. The results at 10 MHz are shown in **Fig. 6** and show a good resolution of bed thickness even for a standoff of 12.7 mm.

[0016] The present disclosure has been made with respect to a wireline implemented device. It may also be adapted for an MWD embodiment using as the carrier a bottomhole assembly conveyed on a drillstring or coiled tubing. It may also be implemented for use on a slickline. It should be noted that for an MWD application, the contact member may be a stabilizer or a steering rib,

[0017] The device may be used to measure any resistivity property of the earth formation. This includes resistivity, conductivity, permittivity and dielectric constant.

[0018] The operation of the transmitter and receivers may be controlled by the downhole processor and/or the surface processor. Implicit in the control and processing of the data is the use of a computer program implemented on a suitable machine readable medium that enables the processor to perform the control and processing. The machine readable medium may include ROMs, EPROMs, EAROMs, Flash Memories and Optical disks.

[0019] While the foregoing disclosure is directed to the specific embodiments of the disclosure, various modifications will be apparent to those skilled in the art. It is intended that all variations within the scope and spirit of the appended claims be embraced by the foregoing disclosure.

CLAIMS

What is claimed is:

1. An apparatus for evaluating an earth formation, the apparatus comprising:

a carrier including a line source of electric current configured to be conveyed in a borehole; and

at least one pair of electrodes proximate to a wall of the borehole, a difference in potential between a first one of the at least one pair of electrodes and a second one of the at least one pair of electrodes being indicative of a resistivity property of the earth formation.

2. The apparatus of claim 1 wherein the line source of electric current further comprises at least one toroidal coil oriented along a longitudinal axis of the borehole.

3. The apparatus of claim 1 wherein the at least one pair of electrodes are disposed on a contact member extendable from the carrier.

4. The apparatus of claim 1 wherein the at least one pair of electrodes further comprises an array of electrodes disposed on a contact member extendable from the carrier.

5. The apparatus of claim 4 wherein the line source of current is disposed on the contact member.

6. The apparatus of claim 5 further comprising an additional line source of current disposed on the contact member, the additional line source of current being inclined to the line source of current.

7. The apparatus of claim 1 further comprising a processor configured to use the difference in potential to estimate a value of the resistivity property.

8. The apparatus of claim 7 wherein the at least one pair of electrodes further comprises a first pair of axially separated electrodes and a second pair of electrodes inclined to the first pair of electrodes and wherein the processor is further configured to estimate the value of the resistivity property in two directions.

9. The apparatus of claim 1 further comprising a conveyance device configured to convey the carrier into the borehole, the conveyance device being selected from: (i) a wireline, (ii) a drillstring, (iii) coiled tubing, and (iv) a slickline.

10. A method of evaluating an earth formation, the method comprising:

activating a line source of electric current conveyed on a carrier in a borehole; and

providing a first signal from a first one of at least one pair of electrodes proximate to a wall of the borehole indicative of a potential of the first one of the electrodes and a second signal from a second one of the at least one pair of electrodes indicative of a potential of the second one of the electrodes; and

using a processor for estimating a resistivity property of the earth formation using the first signal and the second signal.

11. The method of claim 10 further comprising using for the line source of electric current, at least one toroidal coil oriented along a longitudinal axis of the borehole.

12. The method of claim 10 further comprising disposing the at least one pair of electrodes on a contact member extendable from the carrier.

13. The method of claim 10 further comprising using, for the at least one pair of electrodes an array of electrodes disposed on a contact member extendable from the carrier.

14. The method of claim 13 further comprising disposing the line source of current on the contact member.

15. The method of claim 14 further comprising disposing an additional line source of current inclined to the linear source of current on the contact member and wherein the processor is further configured to use an additional first signal

from the first one of the electrodes and an additional second signal from the second one of the electrodes for estimating the value of the resistivity property of the earth formation.

16. The method of claim 10 further comprising:

using, for the at least one pair of electrodes, a first pair of axially separated electrodes and a second pair of electrodes inclined to the first pair of electrodes; and

using the processor for estimating the value of the resistivity property in two directions.

17. The method of claim 10 further comprising using a conveyance device to convey the carrier into the borehole, the conveyance device being selected from: (i) a wireline, (ii) a drillstring, (iii) coiled tubing, and (iv) a slickline.

18. The method of claim 10 wherein the resistivity property is selected from: (i) a resistivity of the formation, (ii) a conductivity of the formation, and (iii) a dielectric constant of the formation.

19. The method of claim 10 wherein the resistivity property further comprises a two-dimensional image of the formation, one axis of the image being depth and a second axis of the image being azimuth.

20. The method of claim 16 further comprising determining an orientation of an anisotropy axis of the earth formation.

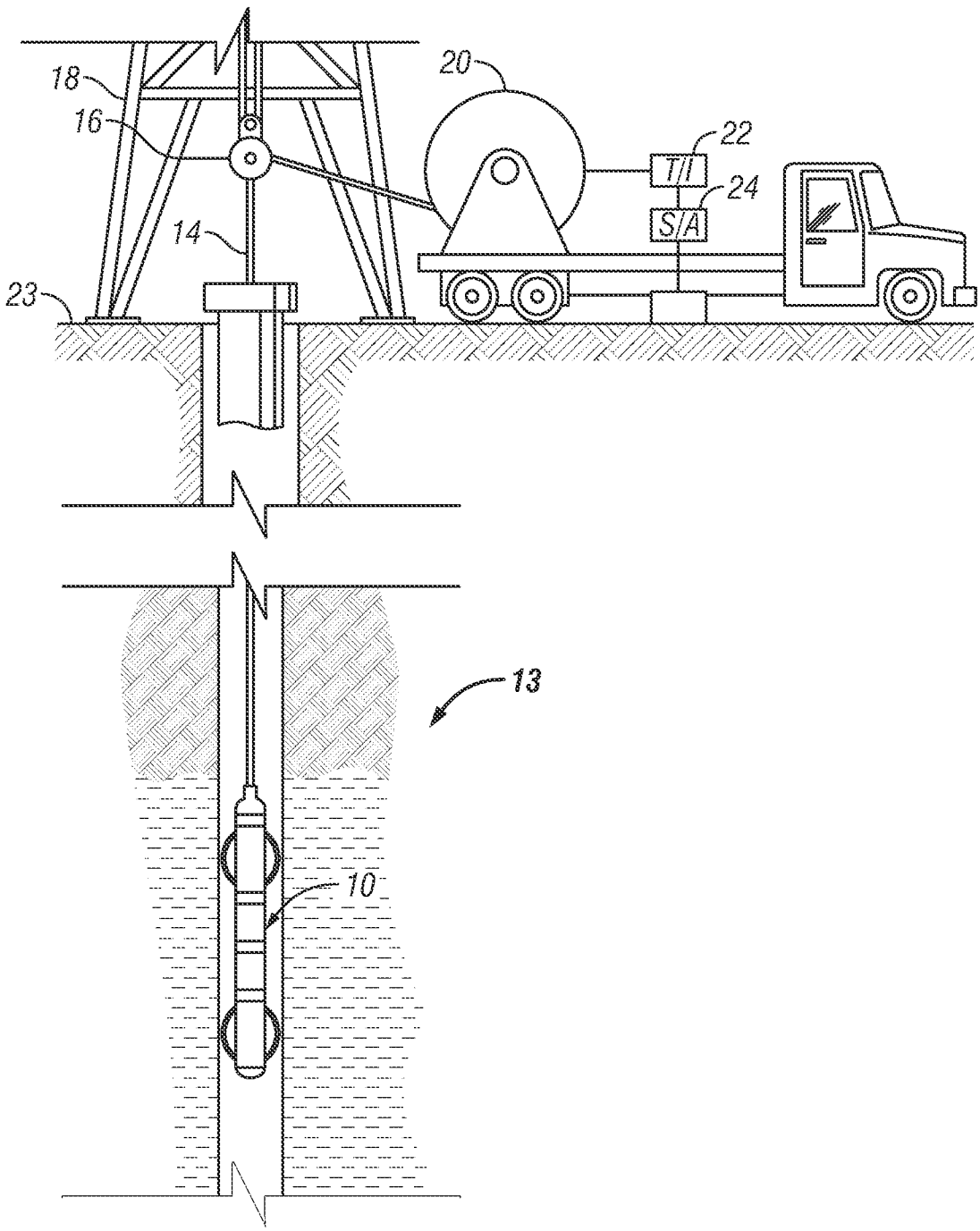


FIG. 1

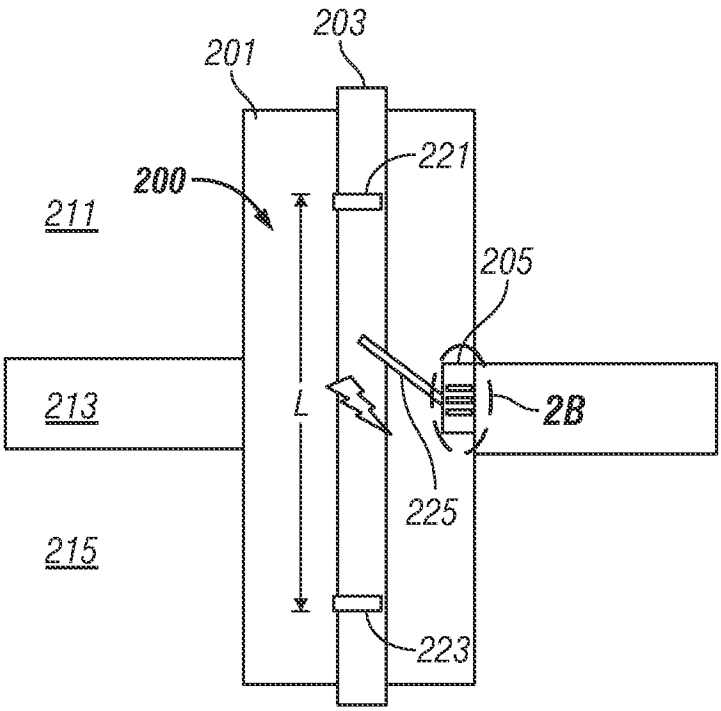

203
201
221
200
211
205
213
L
2B
225
215
223

FIG. 2A

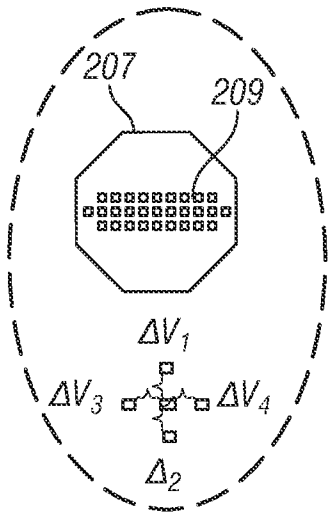

207
209
ΔV_1
ΔV_3
ΔV_4
Δ_2

FIG. 2B

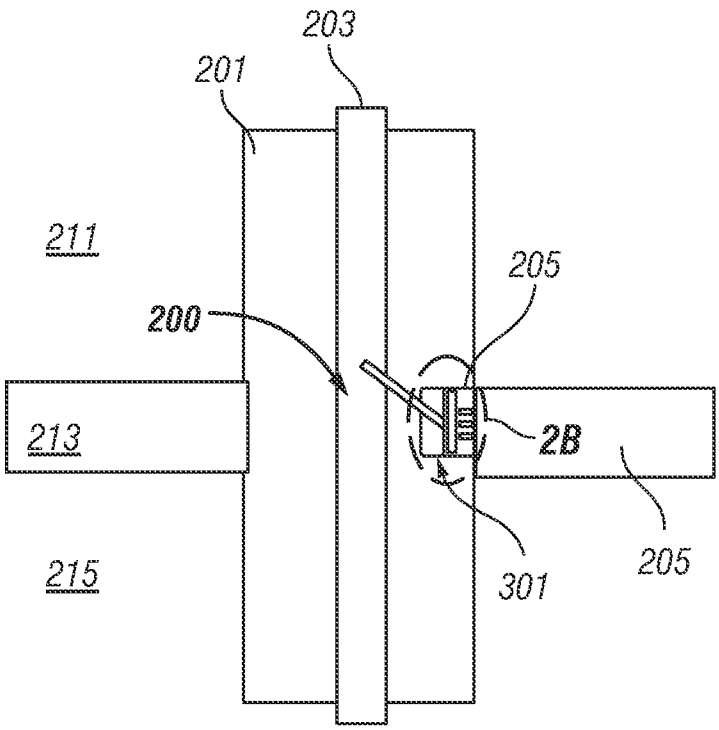


FIG. 3A

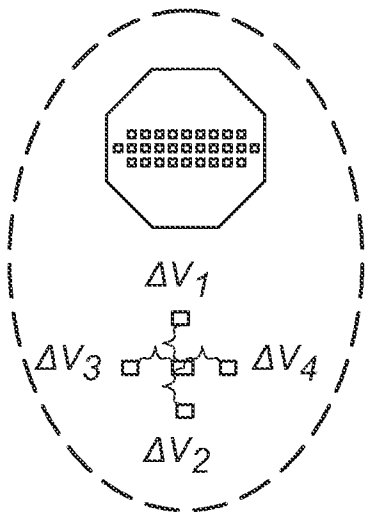


FIG. 3B

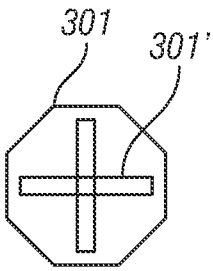


FIG. 3C

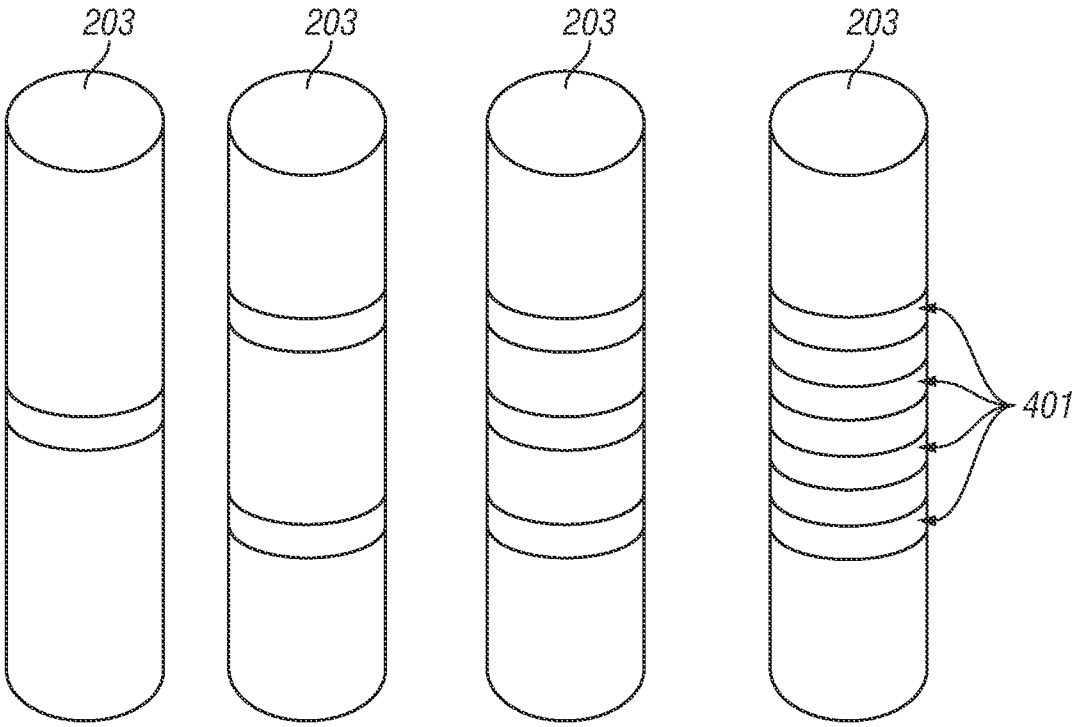


FIG. 4A FIG. 4B FIG. 4C FIG. 4D

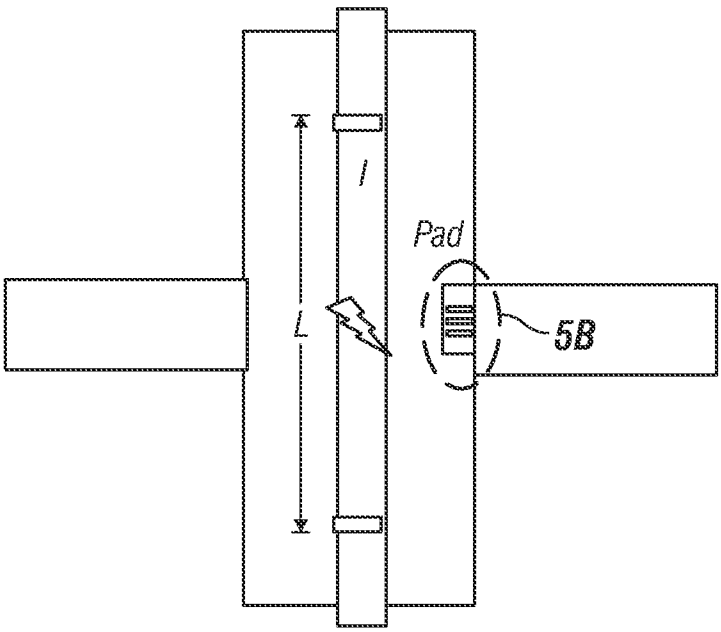


FIG. 5A

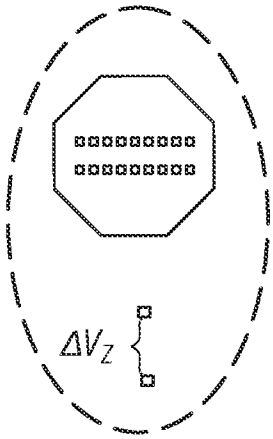


FIG. 5B

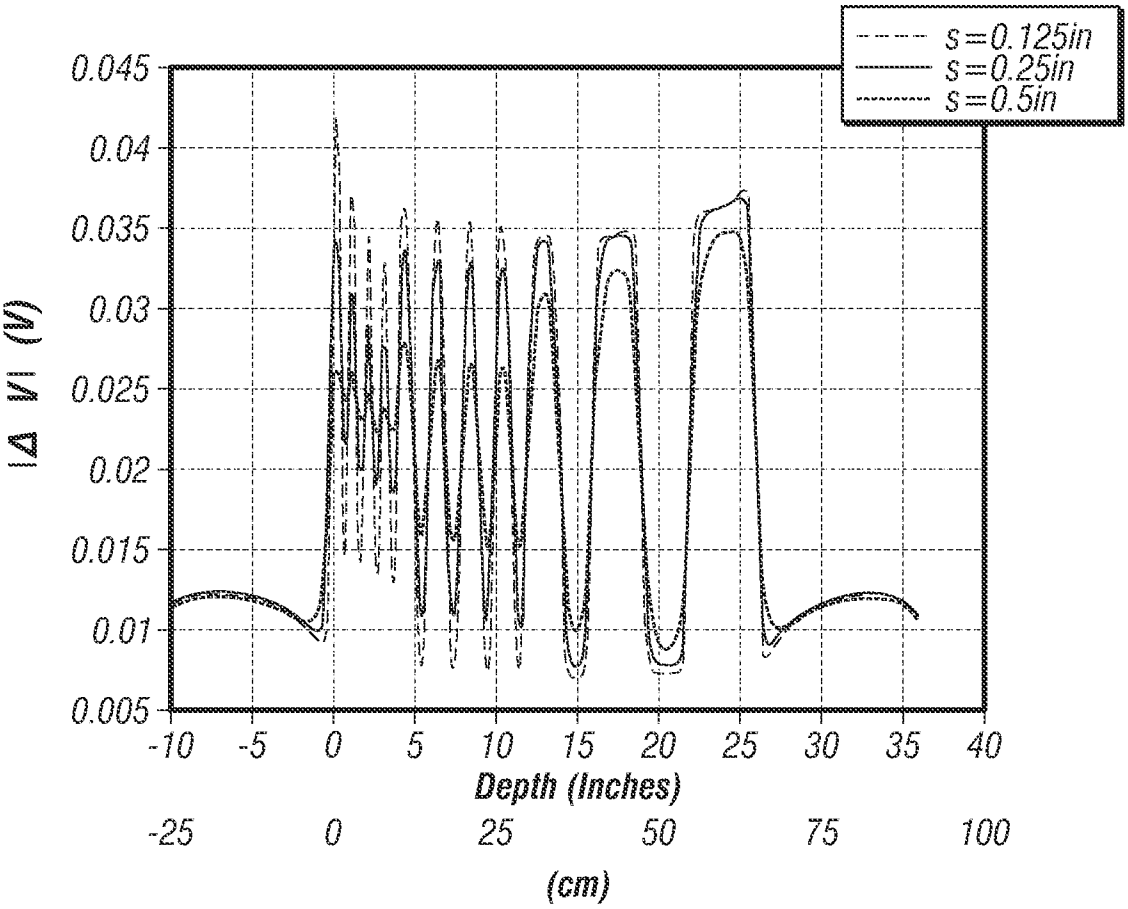

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0.02
0.015
0.01
0.005
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-10
-5
0
5
10
15
20
25
30
35
40
Depth (Inches)
-25
0
25
50
75
100
(cm)

FIG. 6