



(86) Date de dépôt PCT/PCT Filing Date: 2015/12/18
 (87) Date publication PCT/PCT Publication Date: 2016/12/08
 (85) Entrée phase nationale/National Entry: 2017/10/16
 (86) N° demande PCT/PCT Application No.: US 2015/066704
 (87) N° publication PCT/PCT Publication No.: 2016/195753
 (30) Priorités/Priorities: 2015/06/05 (US62/171,398);
 2015/06/05 (US62/171,393)

(51) Cl.Int./Int.Cl. *E21B 10/62* (2006.01),
E21B 10/42 (2006.01), *E21B 10/43* (2006.01)
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(54) Titre : REGION D'OUTIL DE FOND DE TROU MMC COMPRENANT UN MATERIAU ALLOTROPIQUE
 (54) Title: MMC DOWNHOLE TOOL REGION COMPRISING AN ALLOTROPIC MATERIAL

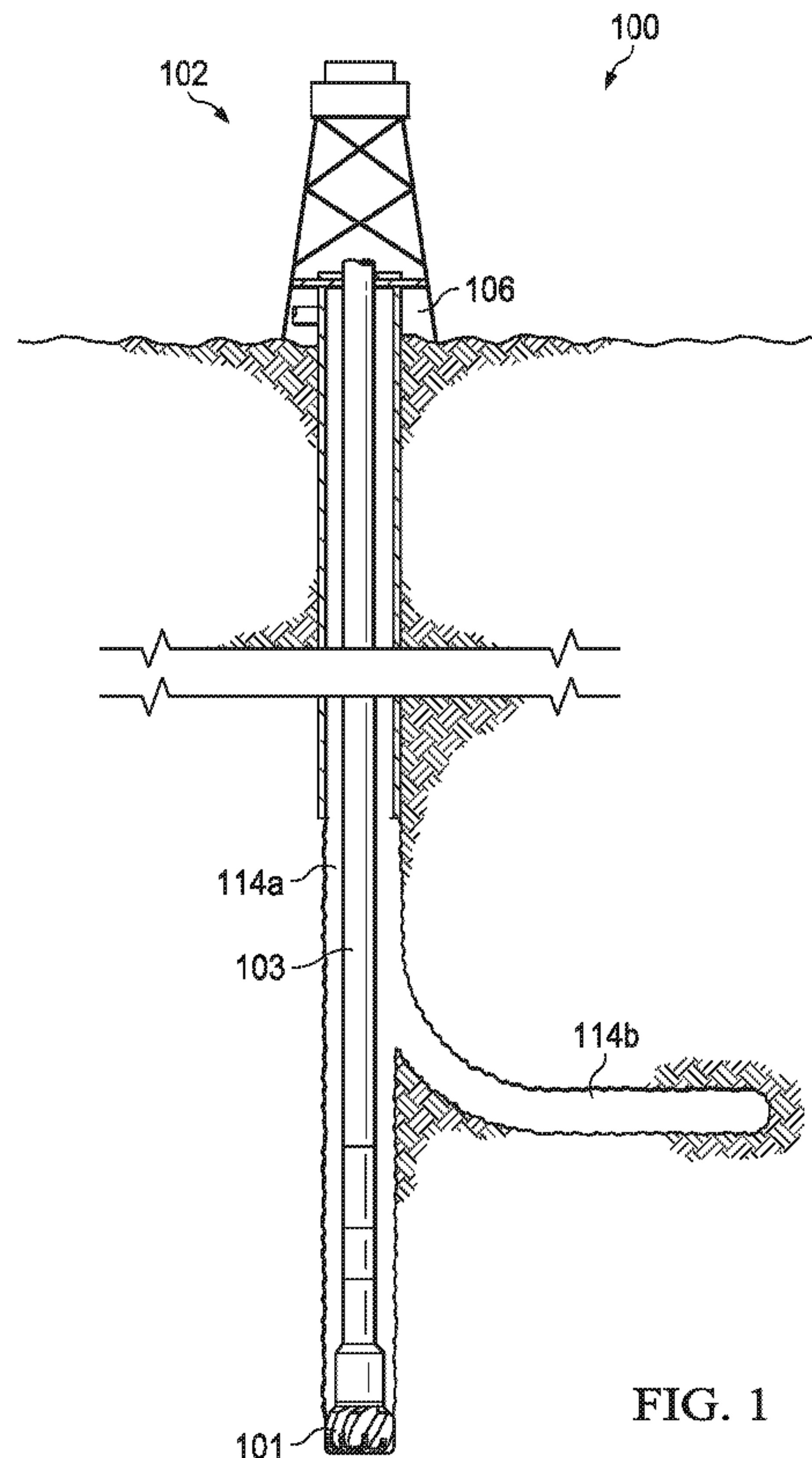


FIG. 1

(57) **Abrégé/Abstract:**

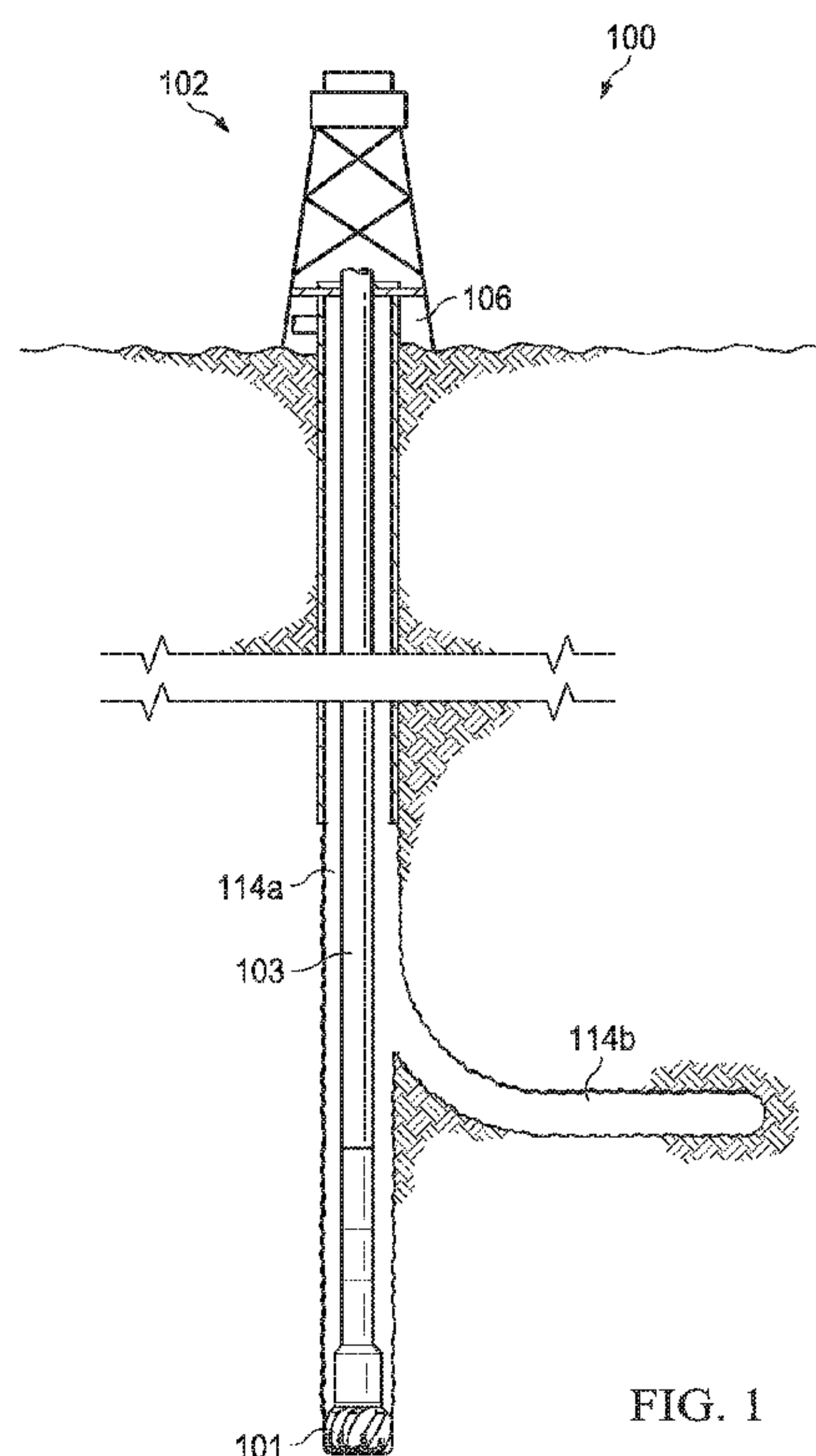
The disclosure provides rotary drill bits with bit head regions or other downhole tools with regions in which an allotropic material in a precursor region has been transformed from a first allotope to a second allotope in response to a trigger. The disclosure further provides methods of forming such downhole tools and methods of triggering an allotropic phase transformation during their use.

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

(19) World Intellectual Property
Organization
International Bureau(43) International Publication Date
8 December 2016 (08.12.2016)(10) International Publication Number
WO 2016/195753 A1

- (51) **International Patent Classification:**
E21B 10/42 (2006.01) *E21B 10/62* (2006.01)
E21B 10/43 (2006.01)
- (21) **International Application Number:**
 PCT/US2015/066704
- (22) **International Filing Date:**
 18 December 2015 (18.12.2015)
- (25) **Filing Language:** English
- (26) **Publication Language:** English
- (30) **Priority Data:**
 62/171,393 5 June 2015 (05.06.2015) US
 62/171,398 5 June 2015 (05.06.2015) 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, BN, 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, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, 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, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, 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,

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(54) **Title:** MMC DOWNHOLE TOOL REGION COMPRISING AN ALLOTROPIC MATERIAL

(57) **Abstract:** The disclosure provides rotary drill bits with bit head regions or other downhole tools with regions in which an allotropic material in a precursor region has been transformed from a first allotope to a second allotope in response to a trigger. The disclosure further provides methods of forming such downhole tools and methods of triggering an allotropic phase transformation during their use.

WO 2016/195753 A1

WO 2016/195753 A1



SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ,
GW, KM, ML, MR, NE, SN, TD, TG).

— *of inventorship (Rule 4.17(iv))*

Declarations under Rule 4.17:

— *as to the identity of the inventor (Rule 4.17(i))*

Published:

— *with international search report (Art. 21(3))*

MMC DOWNHOLE TOOL REGION COMPRISING AN ALLOTROPIC MATERIAL

TECHNICAL FIELD

5 The present disclosure relates generally to rotary drill bits and other downhole tools with an allotropic phase-transformed bit head region or a precursor region able to undergo an allotropic phase transformation in response to a trigger condition.

BACKGROUND

10 Various types of downhole tools are used to form wellbores in downhole formations. These downhole tools including rotary drill bits, reamers, core bits, under reamers, hole openers, and stabilizers. Rotary drill bits include fixed-cutter drill bits, roller cone drill bits, and hybrid drill bits. Rotary drill bits may be manufactured of materials such as polycrystalline diamond compact and metal-matrix composite
15 (MMC). A rotary drill bit may include more than one type of material. For instance PDC drill bits are often also MMC drill bits.

BRIEF DESCRIPTION OF THE DRAWINGS

20 For a more complete understanding of the present invention and its features and advantages, reference is now made to the following description, taken in conjunction with the accompanying drawings, in which:

 FIGURE 1 is an elevation view of a drilling system in which a downhole tool containing a compressive residual strength-hardened region may be used;

25 FIGURE 2 is an isometric view of a fixed-cutter drill bit including a bit head oriented upwardly;

 FIGURE 3 is an isometric view of a blade of the fixed-cutter drill bit of FIGURE 2, with cutter pockets, but with no cutters shown;

 FIGURE 4 is a cross-sectional view of a cutter pocket of FIGURE 3;

30 FIGURES 5A and 5B are cross-sectional views of a curved portion of the fixed-cutter drill bit of FIGURE 2;

FIGURE 6 is a flow chart of a method for creating an allotropic phase-transformed region by inducing an allotropic phase transformation in a precursor region; and

FIGURE 7 is a flow chart of a method for creating an allotropic phase-transformed region during use of a rotary drill bit by inducing an allotropic phase transformation in a precursor region.

DETAILED DESCRIPTION

During a drilling operation, various downhole tools, including drill bits, coring bits, reamers, hole enlargers, or combinations thereof may be lowered into a partially formed wellbore and used to further form the wellbore, for instance by drilling the wellbore deeper into a formation or by increasing the diameter of the wellbore. These downhole tools are subject to a variety of stresses, particularly during contact with the formation. For instance, the shaft of the drill bit may experience different stresses than the head of the bit. Different parts of the bit head may also experience different stresses from one another. The present disclosure provides a rotary drill bit head or other downhole tool portion formed from a metal-matrix composite (MMC) in which an allotropic material in a region of the downhole tool has been transformed from a first allotrope to a second allotrope, thereby altering a physical property of the region. The present disclosure also provides a rotary drill bit head or other downhole tool portion formed from an MMC with a precursor region containing a first allotrope of an allotropic material. During use of the bit head or other downhole tool, if a trigger condition is encountered, the allotropic material transforms to the second allotrope, thereby altering a physical property of the region.

Allotropic materials can have two or more different physical structures while in the same physical state (i.e., solid, liquid, or gas). These different physical structures are referred to as allotropes. The present disclosure relates to allotropic materials with at least two allotropes in the solid state. Often different allotropes in the solid state have different crystal structures, although other differences in physical structure may be found in some allotropic materials. The different physical structures of different allotropes confer different physical properties. Graphite (pencil lead) and diamond are a readily understood examples of how different the physical properties of

different allotropes may be. Although both materials are composed of nearly pure carbon, graphite may be flaked with a fingernail, while diamond is the hardest substance known. The difference is due entirely to the different crystal structures of the two different allotropes.

5 An allotropic phase transformation, as used herein, occurs when an allotropic material changes from one allotrope to another while remaining a solid and without reaction with another chemical. Typically, changing from one allotrope to another causes an increase or a decrease in the atomic packing density, a crystal lattice parameter (if at least one of the allotropes is a crystal), or both. An allotropic phase
10 transformation may be caused by any number of conditions, which commonly include a threshold level of or amount of change in pressure, temperature, or both. For example, the graphite allotrope undergoes an allotropic phase transformation to the diamond allotrope, but only under very high temperature and pressure. Most allotropic phase transformations of interest in forming a downhole tool as disclosed
15 herein do not require such extreme conditions.

Allotropic elements include Americium (Am), Beryllium (Be), Calcium (Ca), Cerium (Ce), Curium (Cm), Cobalt (Co), Dysprosium (Dy), Iron (Fe), Gadolinium (Gd), Hafnium (Hf), Holmium (Ho), Lanthanum (La), Manganese (Mn), Neodymium (Nd), Neptunium (Np), Promethium (Pm), Praseodymium (Pr), Plutonium (Pu), Sulfer
20 (S), Scandium (Sc), Samarium (Sm), Tin (Sn), Strontium (Sr), Terbium (Tb), Thorium (Th), Titanium (Ti), Uranium (U), Yttrium (Y), Ytterbium (Yb), and Zirconium (Zr). Allotropic materials include alloys of any of these allotropic elements, such as steel (Fe-C), in which the allotropic element may still be present as at least two different allotropes.

25 Allotropes may be detected and distinguished from one another using any of a variety of known non-destructive or destructive measurement methods. For instance allotropes may be distinguished using X-ray diffraction.

According to the present disclosure, a precursor region is formed on a bit head or other downhole tool portion. The precursor region may be formed when the portion
30 is formed, prior to formation of a downhole tool with the portion, during formation of a downhole tool with the portion, or after formation of the downhole tool on the portion, but before use of the downhole tool. The precursor region includes an

allotropic material that can undergo an allotropic phase transformation in response to a trigger condition to cause a change in a physical property of the region.

Typically at least one physical property of the region that is changed relates to the stress in the region, which tends to become more or less compressive or tensile depending on whether the region was under a compressive or tensile stress prior to the allotropic phase transformation and whether the second allotrope has a lower or higher packing density or shorter or longer length of at least one lattice parameter. These changes in the stress of the region may change other properties of the region, such as its hardness or its crack-resistance.

In one example, the region may be a precursor region containing a first allotrope of a metal. When the precursor region encounters heat above a certain temperature, either during manufacture or use of the downhole tool, the metal transforms to a second allotrope. The first allotrope has a lower packing density, at least one shorter lattice parameter (if a crystal), or both than the second allotrope. The allotropic material is a solid and is constrained in at least one dimension such that the second allotrope occupies the same physical space as the first allotrope, so a compressive residual stress is created in the region. The region thus becomes compressive residual-stress hardened.

For example, the precursor region may include the austenite allotrope of Fe, which has a face centered cubic (FCC) crystal structure. When the precursor region is cooled, the Fe undergoes an allotropic phase transformation to the ferrite allotrope, which has a body centered cubic (BCC) crystal structure. The ferrite allotrope of Fe has a lower packing density than the austenite allotrope, so a residual compressive stress in the region is created by the allotropic phase transformation. In other examples, after the Fe undergoes an allotropic phase transformation to a ferrite allotrope, the Fe may have entrapped carbon and have a body centered tetragonal (BCT) crystal structure.

Various methods for measuring compressive residual stress are known. Methods, such as X-ray diffraction and hardness profile testing, are compatible with measuring compressive residual stress in the present disclosure. X-ray diffraction may also be used to determine the allotrope present in any portion of the downhole tool. Although some testing may be non-destructive, such as X-ray diffraction measured on

the surface of a region, other testing, such as testing of the interior of a region or hardness testing, may be destructive. If destructive testing is used to determine compressive residual stress of an allotrope, then representative samples may be used and the test results may be assumed to apply to other downhole tools of the same construction formed in the same way.

A compressive residual stress increases crack-resistance of a region as compared to a similar region that did not undergo an allotropic phase transformation or another region that does not contain the allotropic material. Compressive residual stress helps arrest any cracks that may form or propagate by essentially squeezing the crack, especially at its ends. Crack-resistance may be measured using any of a number of known measurements techniques, which are usually not dependent on how the material was formed. Crack-resistance may focus on the ability to resist propagation of cracks that have formed, rather than the ability to resist formation of cracks in the first place. Cracks in a downhole tool may be detected using any of a number of known detection techniques including fluorescent-penetrant dye inspection, ultrasonic testing, and X-ray testing.

A compressive residual stress in a region may also improve its erosion resistance, stiffness, strength, toughness, or any combination thereof. These improved properties may be achieved instead of or in addition to improved crack-resistance as compared to a similar region that did not undergo an allotropic phase transformation or another region of the bit head that does not contain the allotropic material. These properties may also be measured using known measurement techniques, which are also not usually dependent on how the material was formed.

Typically the compressive residual stress-hardened region includes part of a surface of the downhole tool and also extends into the tool. Typically, the compressive residual stress-hardened region extends into the downhole tool at least 0.1 mm, at least 1 mm, at least 10 mm, or at least 250 mm, as well as between any combinations of these endpoints.

In another example, the precursor region may include a first allotrope of an allotropic material that transforms to the second allotrope in response to a strain, such as a strain caused by a crack. The first allotrope has a higher packing density, at least one shorter lattice parameter (if a crystal), or both than the second allotrope and both

the first and second allotropes occupy the same physical space, so the transformation creates a compressive force in the area of the strain that helps relieve the strain, arrest the crack, or both. Although the allotropic phase transformation may be triggered at any time, it is often triggered by strains generated during use of the downhole tool.

5 After the allotropic phase transformation has occurred, the region may exhibit increased erosion- and crack-resistance, stiffness, strength, and ductility along its surface as compared to regions that lack the allotropic material or in which the phase transformation has not occurred.

Suitable allotropic materials for use in this example include zirconium dioxide
10 (ZrO_2). An allotropic phase transformation may be triggered in these materials by a temperature decrease as well as by strain. As a result, they may undergo the transformation at an undesirable time, such as prior to use of the downhole tool. In addition, when these materials undergo an allotropic phase transformation as a result of cooling, the allotropic material may expand to the point where it cracks. To avoid a
15 cooling-triggered allotropic phase transformation, a phase-stabilization material may be added to the allotropic material to suppress the allotropic phase transformation. Suitable phase-stabilization materials for use with zirconia include yttrium oxide (Y_2O_3), cerium oxide (CeO_2), magnesium oxide (MgO), calcium oxide (CaO), and any combinations thereof. Phase-stabilization materials may be used with other
20 allotropic materials as well. They may be coated onto the precursor region or they may be part of the precursor region when it is formed.

Phase-stabilization materials may also be used to control the depth to which an allotropic phase transformation may occur. As further illustrated in FIG. 5 the phase-stabilization material may be located below the precursor region in a downhole tool,
25 allowing the allotropic phase to transform only in the overlying precursor region.

Although the downhole tools and methods discussed herein refer to a single precursor region and single compressive residual stress-hardened region for simplicity, a bit head, including a single part of the bit head, may include a plurality of such regions. Furthermore, different precursor regions or corresponding
30 compressive residual stress-hardened regions or even the same precursor region or compressive residual stress-hardened region may contain different allotropic materials. In addition, different precursor regions and different compressive residual

stress-hardened regions may be formed at different times and different types of heating or multiple heating steps may be used to cause an allotropic phase transformation in different precursor regions or different allotropic materials. Furthermore, although the allotropic material is referred to herein as occupying the same physical space after the allotropic phase transformation, some variation in physical dimensions, particularly in directions where the material is not constrained, may occur. Typically this variation in any direction will be less than 1% of the length of that direction, or the volume occupied by the first allotrope will not change by more than 10%.

Aspects of the present disclosure and its advantages may be better understood by referring to FIGURES 1 through 7, where like numbers are used to indicate like and corresponding parts.

FIGURE 1 is an elevation view of a drilling system in which a downhole tool containing a hardened region may be used. Drilling system 100 includes a well surface or well site 106. Various types of drilling equipment such as a rotary table, drilling fluid pumps and drilling fluid tanks (not expressly shown) may be located at well surface or well site 106. For example, well site 106 may include drilling rig 102 that may have various characteristics and features associated with a land drilling rig. However, downhole tools incorporating teachings of the present disclosure may be satisfactorily used with drilling equipment located on offshore platforms, drill ships, semi-submersibles, and/or drilling barges (not expressly shown).

When configured for use with a drill bit, drilling system 100 includes drill string 103 associated with drill bit 101, typically through a bottom hole assembly (BHA). The drilling system is used to form a wide variety of wellbores or bore holes such as generally vertical wellbore 114a or directional wellbore, such as generally horizontal wellbore 114b, or any combination thereof. Drilling system 100 may be configured in alternative ways for other downhole tools having a shaft.

In the present disclosure, drill bit 101 or another downhole tool in drilling system 100 includes a compressive residual stress-hardened region on its head. The compressive residual stress-hardened region may optimize drill bit 101 or other downhole tool for the conditions experienced during the drilling operation to increase the life span of drill bit 101 or other downhole tool. Although drill bit 101 is depicted

as a fixed-cutter drill bit, any drill bit having a head with a compressive residual stress-hardened region may be used in drilling system 100.

FIGURE 2 is an isometric view of fixed-cutter drill bits oriented upwardly. Drill bit 101 formed in accordance with teachings of the present disclosure may have many different designs, configurations, and dimensions according to the particular application of drill bit 101.

Drill bit 101 includes shaft 151 and head 150. Shaft 151 includes shank 152 with threaded connector 155. Shank 152 is securely attached to head 150 such that it will not separate from head 150 during normal operation of drill bit 101. Threaded connector 155 [also referred to as an American Petroleum Institute (API) connector] may be used to releasably engage drill bit 101 with drill string 103 or FIGURE 1, typically through the BHA. When engaged with drill string 103, drill bit 101 may be rotated relative to bit rotational axis 104.

Drill bit 101 includes head 150 including one or more blades 126a–126g, collectively referred to as blades 126, that are disposed outwardly from exterior portions of rotary bit body 124. Rotary bit body 124 may have a generally cylindrical body and blades 126 may be any suitable type of projections extending outwardly from rotary bit body 124. For example, a part of blade 126 may be directly or indirectly coupled to an exterior portion of bit body 124, while another part of blade 126 may be projected away from the exterior portion of bit body 124. Blades 126 formed in accordance with the teachings of the present disclosure may have a wide variety of configurations including substantially arched, helical, spiraling, tapered, converging, diverging, symmetrical, asymmetrical, or any combinations thereof.

Each of blades 126 may include a first end disposed proximate or toward bit rotational axis 104 and a second end disposed proximate or toward exterior portions of drill bit 101 (i.e., disposed generally away from bit rotational axis 104 and toward uphole portions of drill bit 101). Blades 126 may have apex 142 that may correspond to the portion of blade 126 furthest from bit body 124 and blades 126 may join bit body 124 at landing 145. Exterior portions of blades 126, cutters 128 and other suitable elements may be described as forming portions of the bit face.

Plurality of blades 126a–126g may have respective junk slots or fluid-flow paths 140 disposed therebetween. Drilling fluids are communicated through one or more nozzles 156.

Although bit body 124 and blades 126 may be formed from any material, typically they are formed from a reinforcement material infiltrated with a binder. Any part of bit head 150, including multiple parts thereof, may contain a precursor region or allotropic phase-transformed region.

FIGURE 3 is an isometric view of a blade of the fixed-cutter drill bit of FIGURE 2, with cutter pockets, but with no cutters shown. Cutter pockets 160 are one example of a portion of blade 126 that is a precursor region or an allotropic phase-transformed region. Cutter pockets 160 may have a higher crack resistance, a higher erosion resistance, a greater stiffness, a greater strength, a greater ductility, a greater toughness or any combination thereof as compared to another portion of blade 126 that is not a precursor region or an allotropic phase-transformed region. Cutter pockets 160, particularly when combined with a softer underlying material, may result in an increased lifespan for blade 126 as cutter pockets are prone to failure due to cracks, fatigue, or both.

FIGURE 4 is a cross-sectional view of a cutter pocket of FIGURE 3. Typically the precursor region or allotropic phase-transformed region of cutter pocket 160 includes part of a surface of cutter pocket 160 and also extends into the tool by a thickness 170. Thickness 170 of the precursor region or allotropic phase-transformed region of cutter pocket 160 may be a function of the diameter of cutter pocket 160. For example, as the diameter increases, thickness 170 may also increase. Typically, thickness 170 may be at least 0.1 mm, at least 1 mm, at least 10 mm, or at least 250 mm, as well as between any combinations of these endpoints.

While FIGURE 4 illustrates the precursor region or allotropic phase-transformed region with respect to cutter pocket 160, other portions of the bit head, such as the nozzle channels, may include one or more precursor regions or one or more allotropic phase-transformed regions.

FIGURE 5A is a cross-sectional view of a curved portion of the fixed-cutter drill bit of FIGURE 2. Phase-stabilization material 180a may be added to a portion of the drill bit to control thickness 170a of the allotropic-phase transformed region or a

portion of the precursor region that has undergone an allotropic phase transformation in response to a drilling condition, such as a crack by preventing the allotropic phase transformation from extending past phase-stabilization material 180a. Phase-stabilization material 180a may be any suitable phase-stabilization material including yttrium oxide (Y_2O_3), cerium oxide (CeO_2), magnesium oxide (MgO), calcium oxide (CaO), and any combinations thereof. Phase-stabilization material 180a may be coated onto the region or may be part of the region when it is formed.

FIGURE 5B is another cross-sectional view of a curved portion of the fixed-cutter drill bit of FIGURE 2. Allotropic material may be added to only a portion of the drill bit, such as inner region 180b, to control thickness, position, or location of the outer region 170b. In this manner, outer region 170b may be free of allotropic material. Such a configuration may maintain certain properties of outer region 170b, such as ductility, while preventing cracks that may form from propagating past inner region 180b.

To form an MMC downhole tool, a mold is formed by milling a block of material, such as graphite, to define a mold cavity having features that correspond generally with the exterior features of drill bit 101. Various features of drill bit 101 including blades 126, cutter pockets 160, fluid-flow passageways, or combinations thereof are provided by shaping the mold cavity, by positioning temporary displacement materials within interior portions of the mold cavity, or both. Precursor regions near these features, particularly cutter pockets and fluid-flow passageways, may be formed by placing an allotropic material adjacent to or in the vicinity of the displacement materials. Alternatively, if allotropic material should not be exposed to infiltration conditions or the binder, displacement materials may be placed in the allotropic phase-transformed regions, then removed so that the regions may be filled with allotropic material. As another alternative, the precursor region may be formed by coating a region of a formed bit head. The coating may be applied using any suitable application technique, including spraying the coating on the precursor region, dipping the precursor region into a liquid coating, or any combination thereof. Such a coating may also be diffused into the downhole tool.

As noted above, a phase-stabilization material may also be included in or near the precursor region. The phase-stabilization material may simply be mixed with the

material that forms the precursor region prior to its formation, it may be placed below the precursor region in the mold, or it may be coated onto the precursor region after its formation. If coated, the coating may be performed using any method described above. Alternatively, the tungsten carbide powder may be coated with an allotropic material that may interact with either the powder or binder material to produce an allotropic phase transformation.

If the allotropic material in the precursor region is transformed prior to use of the downhole tool, then, regardless of when or how it is formed, at some point prior to the completion of manufacturing and eventual use of the downhole tool, the precursor region is subjected to a trigger condition, such as heat, to cause an allotropic phase transformation of the allotropic material.

FIGURE 6 is a flow chart of one such method 600. The steps of method 600 may be performed by a person or manufacturing device that is configured to identify precursor regions and create conditions that transform the allotropic phase of the allotropic material in that region. Either the person or the manufacturing device may be referred to as a manufacturer.

In step 602 the manufacturer identifies a precursor region on bit head 150, particularly on a metallic portion of bit head 150. The precursor region includes a first allotrope of an allotropic material identified herein. In step 604, the precursor region is subjected to a trigger condition to cause an allotropic phase transformation, which forms an allotropic phase-transformed region with a second allotrope of the allotropic material.

One trigger condition particularly useful with allotropic materials containing metals is heating. Heating may include induction, flame, laser, electron beam, thermal radiation, convection, friction, or combinations thereof. Induction heating is the process of heating an object through electromagnetic induction. Flame heating is the process of heating an object by exposing the object to a torch or flame. Laser heating is the process of heating an object with a laser beam. Electron beam heating is the process of heating an object by exposing an object to an electron beam. Thermal radiation heating is the process of an object by exposing the object to heat radiating off of another object. Convection heating is the process of heating an object by exposing the object to air currents that have been circulated over a heating element.

Friction heating is the process of heating an object by exposing the object to heat generated by friction between the object and another object. Another trigger condition is the combination of heating and quenching where the allotropic material is heated followed by quenching to rapidly cool the allotropic material to finish the allotropic phase transformation.

Heating may also or alternatively include carburizing, nitriding, boronizing, or combinations thereof. Carburizing, nitriding, and boronizing further increase the compressive residual stress by introducing carbon (C), nitrogen (N), or boron (B) as an interstitial element in the compressive residual strength-hardened region. In any of the three processes, the allotropic material is heated in the presence of another material with a high carbon, nitrogen, or boron content for carburizing, nitriding, or boronizing, respectively. The amount of carbon, nitrogen, or boron content absorbed by the allotropic material varies based on the temperature to which the material is heated and the elapsed time of the heating. Additionally, higher temperatures and longer elapsed time may increase the depth of interstitial element absorption in the allotropic material. After heating, the precursor region is rapidly cooled to cause an allotropic phase transformation in the allotropic material.

The compressive residual stress in a compressive residual strength-hardened region may also be further increased by shot peening the region or the part of the bit head containing the region. During shot peening, the surface of the precursor region is impacted by hard particles with a force sufficient to cause the surface to be plastically deformed. The plastic deformation creates a compressive residual stress on the surface and also creates tensile stress in the interior. Other trigger conditions may include cooling, applied stress (compressive or tensile), crack propagation, or an applied strain.

The allotropic material in the precursor region may be transformed during use of the downhole tool in response to a trigger condition. FIGURE 7 is a flow chart of a method for creating an allotropic phase-transformed region during use of a rotary drill bit by inducing an allotropic phase transformation in a precursor region. The steps of method 700 may be performed by a person or equipment that is configured to perform a drilling operation. Either the person or the equipment may be referred to as an operator.

In step 702, the operator may contact a subterranean formation with a rotary drill bit. The rotary drill bit contains a precursor region. The precursor region is not subjected to a trigger condition to cause an allotropic phase transformation prior to use. At step 704, if a trigger condition is encountered by the rotary drill bit, the trigger condition induces an allotropic phase transformation in the precursor region at step 708. Trigger conditions often include strain or tensile stresses created by cracks or temperature changes due to the environment in the wellbore. The allotropic phase transformation may occur in only a part of the region that experiences the trigger condition during use of the downhole tool. If a trigger condition is not encountered by the rotary drill bit, the precursor region of the drill bit remains unchanged, at step 706, and the drill bit continues the drilling operation until a trigger is encountered.

Embodiments disclosed herein include:

A. A downhole tool including an allotropic phase-transformed region in which the allotropic phase-transformed region results at least in part from a second allotrope of an allotropic material occupying the same location as was occupied by a first allotrope of the allotropic material prior to an allotropic phase transformation.

B. A downhole tool including a precursor region, wherein the precursor region contains a first allotrope of an allotropic material that is able to undergo an allotropic phase transformation to a second allotrope when a trigger condition is encountered.

C. A method of increasing crack resistance of a downhole tool by forming a precursor region in the downhole tool, wherein the precursor region contains a first allotrope of an allotropic material that is able to undergo an allotropic phase transformation to a second allotrope in response to a strain caused by a crack in the first allotrope to create an allotropic phase-transformed region. D. A downhole tool including a precursor region containing a first allotrope of an allotropic material that is able to undergo an allotropic phase transformation to a second allotrope in response to a strain caused by a crack in the first allotrope to create an allotropic phase-transformed region.

E. A method of hardening a bit head region of a downhole drill bit by heating a precursor region on the bit head to transform a first allotrope of an allotropic material in the precursor region to a second allotrope in the same physical space,

thereby causing a compressive residual stress in the precursor region and hardening it to form a corresponding compressive residual stress-hardened region.

Each of embodiments A, B, C, D, and E may have one or more of the following additional elements in any combination, so long as such combination is not clearly impossible: i) the second allotrope may have a decreased atomic packing density as compared to the first allotrope; ii) the allotropic material may include Americium (Am), Beryllium (Be), Calcium (Ca), Cerium (Ce), Curium (Cm), Cobalt (Co), Dysprosium (Dy), Iron (Fe), Gadolinium (Gd), Hafnium (Hf), Holmium (Ho), Lanthanum (La), Manganese (Mn), Neodymium (Nd), Neptunium (Np), Promethium (Pm), Praseodymium (Pr), Plutonium (Pu), Sulfur (S), Scandium (Sc), Samarium (Sm), Tin (Sn), Strontium (Sr), Terbium (Tb), Thorium (Th), Titanium (Ti), Uranium (U), Yttrium (Y), Ytterbium (Yb), Zirconium (Zr), Am alloy, Be alloy, Ca alloy, Ce alloy, Cm alloy, Co alloy, Dy alloy, Fe alloy, Gd alloy, Hf alloy, Ho alloy, La alloy, Mn alloy, Nd alloy, Np alloy, Pm alloy, Pr alloy, Pu alloy, S alloy, Sc alloy, Sm alloy, Sn alloy, Sr alloy, Tb alloy, Th alloy, Ti alloy, U alloy, Y alloy, Yb alloy, or Zr alloy; iii) the first allotrope may include the austenite allotrope of iron (Fe) and has a face centered cubic (FCC) crystal structure; iv) the second allotrope may include the ferrite allotrope of Fe and has a body centered cubic (BCC) crystal structure; v) the second allotrope may include the ferrite allotrope of Fe with entrapped carbon (C) and has a body centered tetragonal (BCT) crystal structure; vi) the allotropic phase-transformed region may have a decreased atomic packing density causing a compressive residual stress; vii) the second allotrope may have a decreased atomic packing density as compared to the first allotrope; viii) the allotropic material may be zirconium dioxide; ix) a phase-stabilization material may be located under the surface of the allotropic phase-transformed region or the precursor region; x) the phase-stabilization material may be at least one of yttrium oxide, cerium oxide, magnesium oxide, calcium oxide; xi) crack resistance may further include transforming the first allotrope to the second allotrope when a trigger condition is encountered; xii) the first allotrope may transform to the second allotrope only in a portion of the precursor region, such as a portion proximate a crack; xiii) the allotropic phase transformation may be halted at a phase-stabilization region below the precursor region; xiv) an allotropic material located under the exterior surface of the tool.

Although the present disclosure and its advantages have been described in detail, it should be understood that various changes, substitutions and alterations can be made herein without departing from the spirit and scope of the disclosure as defined by the following claims. It is intended that the present disclosure encompasses
5 such changes and modifications as fall within the scope of the appended claims. For instance, one of ordinary skill in the art may apply the teachings herein to other downhole tool portions such as portions of the bit shaft or portions of a downhole tool other than a rotary drill bit. Such other downhole tool portions may have allotropic phase-transformed regions similar to those described herein for the bit head and
10 formed using the methods described herein.

WHAT IS CLAIMED IS:

1. A method of increasing crack resistance of a downhole tool, the method comprising forming a precursor region in the downhole tool, wherein the precursor region contains a first allotrope of an allotropic material that is able to
5 undergo an allotropic phase transformation to a second allotrope in response to a strain caused by a crack in the first allotrope to create an allotropic phase-transformed region.
2. The method of claim 1, further comprising transforming the first
10 allotrope to the second allotrope when in response to the strain.
3. The method of claim 2, wherein the first allotrope transforms to the second allotrope only in a portion of the precursor region proximate the crack.
- 15 4. The method of claim 2, further comprising halting the allotropic phase transformation at a phase-stabilization region below the precursor region.
5. The method of claim 1, wherein the allotropic material is zirconium
20 dioxide.
6. The method of claim 4, wherein the phase-stabilization region
comprises a phase-stabilization material located under a surface of the allotropic phase-transformed region or an allotropic material located under an exterior of the
25 downhole tool.
7. The method of claim 6, wherein the phase-stabilization material
comprises at least one of yttrium oxide, cerium oxide, magnesium oxide, calcium
oxide.
- 30 8. A downhole tool comprising a precursor region containing a first
allotrope of an allotropic material that is able to undergo an allotropic phase

transformation to a second allotrope in response to a strain caused by a crack in the first allotrope to create an allotropic phase-transformed region.

9. The downhole tool of claim 8, further comprising an allotropic phase-
5 transformed region in which the first allotrope has transformed to the second allotrope in response to the strain.

10. The downhole tool of claim 9, wherein the allotropic phase-
transformed region is proximate the crack.

10

11. The downhole tool of claim 8, a phase-stabilization region below the precursor region.

12. The downhole tool of claim 8, wherein the allotropic material is
15 zirconium dioxide.

13. The downhole tool of claim 11, wherein the phase-stabilization region comprises a phase-stabilization material located under a surface of the allotropic phase-transformed region or an allotropic material located under an exterior of the
20 downhole tool.

14. The downhole tool of claim 13, wherein the phase-stabilization material comprises at least one of yttrium oxide, cerium oxide, magnesium oxide, calcium oxide.

25

15. A method of hardening a bit head region of a downhole drill bit, the method comprising heating a precursor region on the bit head to transform a first allotrope of an allotropic material in the precursor region to a second allotrope in the
30 same physical space, thereby causing a compressive residual stress in the precursor region and hardening it to form a corresponding compressive residual stress-hardened region.

16. The method of claim 15, wherein the second allotrope has a decreased atomic packing density as compared to the first allotrope, causing the compressive residual stress.

5

17. The method of claim 15, wherein heating comprises induction, flame, laser, electron beam, thermal radiation, convection, friction, or combinations thereof.

18. The method of claim 15, wherein heating comprises carburizing,
10 nitridizing, boronizing, or combinations thereof.

19. The method of claim 15, wherein the first allotrope comprises the austenite allotrope of iron (Fe) and has a face centered cubic (FCC) crystal structure, and the second allotrope comprises the ferrite allotrope of Fe and has a body centered
15 cubic (BCC) crystal structure.

20. The method of claim 15, wherein the first allotrope comprises the austenite allotrope of iron (Fe) and has a face centered cubic (FCC) crystal structure, and the second allotrope comprises the ferrite allotrope of Fe with entrapped carbon
20 (C) and has a body centered tetragonal (BCT) crystal structure.

21. The method of claim 15, wherein the allotropic material comprises Americium (Am), Beryllium (Be), Calcium (Ca), Cerium (Ce), Curium (Cm), Cobalt (Co), Dysprosium (Dy), Iron (Fe), Gadolinium (Gd), Hafnium (Hf), Holmium (Ho),
25 Lanthanum (La), Manganese (Mn), Neodymium (Nd), Neptunium (Np), Promethium (Pm), Praseodymium (Pr), Plutonium (Pu), Sulfur (S), Scandium (Sc), Samarium (Sm), Tin (Sn), Strontium (Sr), Terbium (Tb), Thorium (Th), Titanium (Ti), Uranium (U), Yttrium (Y), Ytterbium (Yb), Zirconium (Zr), or an alloy thereof.

30

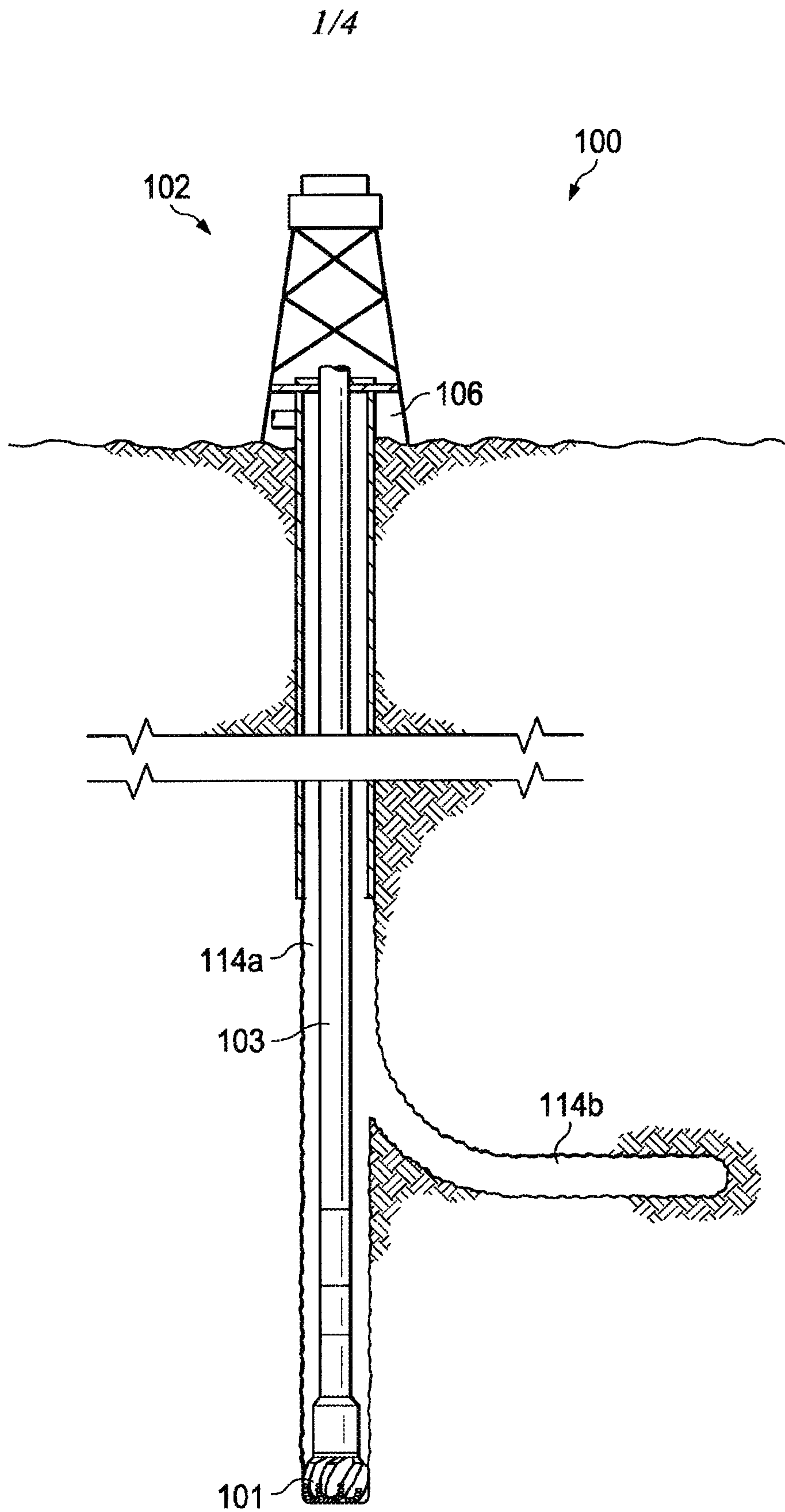


FIG. 1

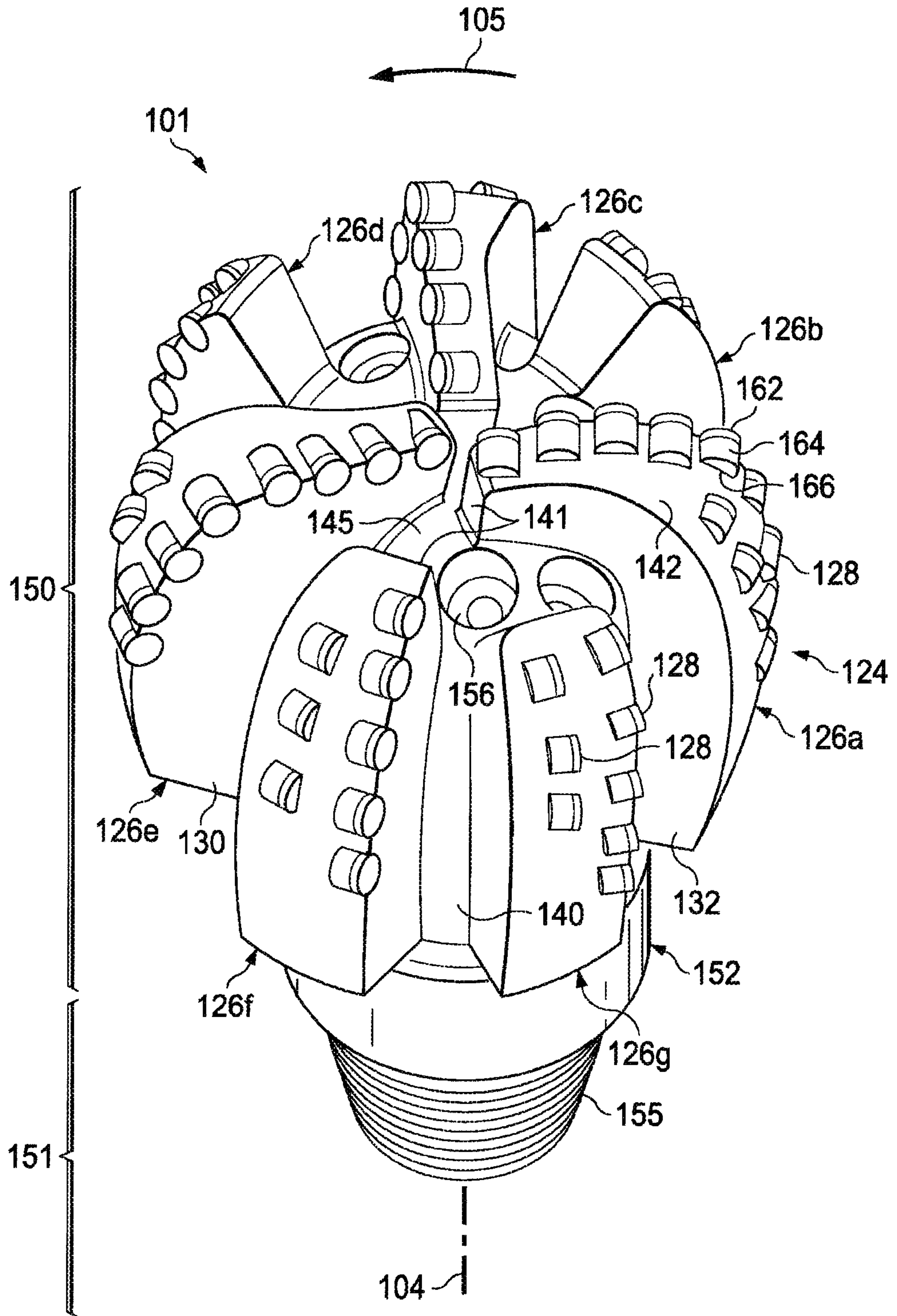


FIG. 2

3/4

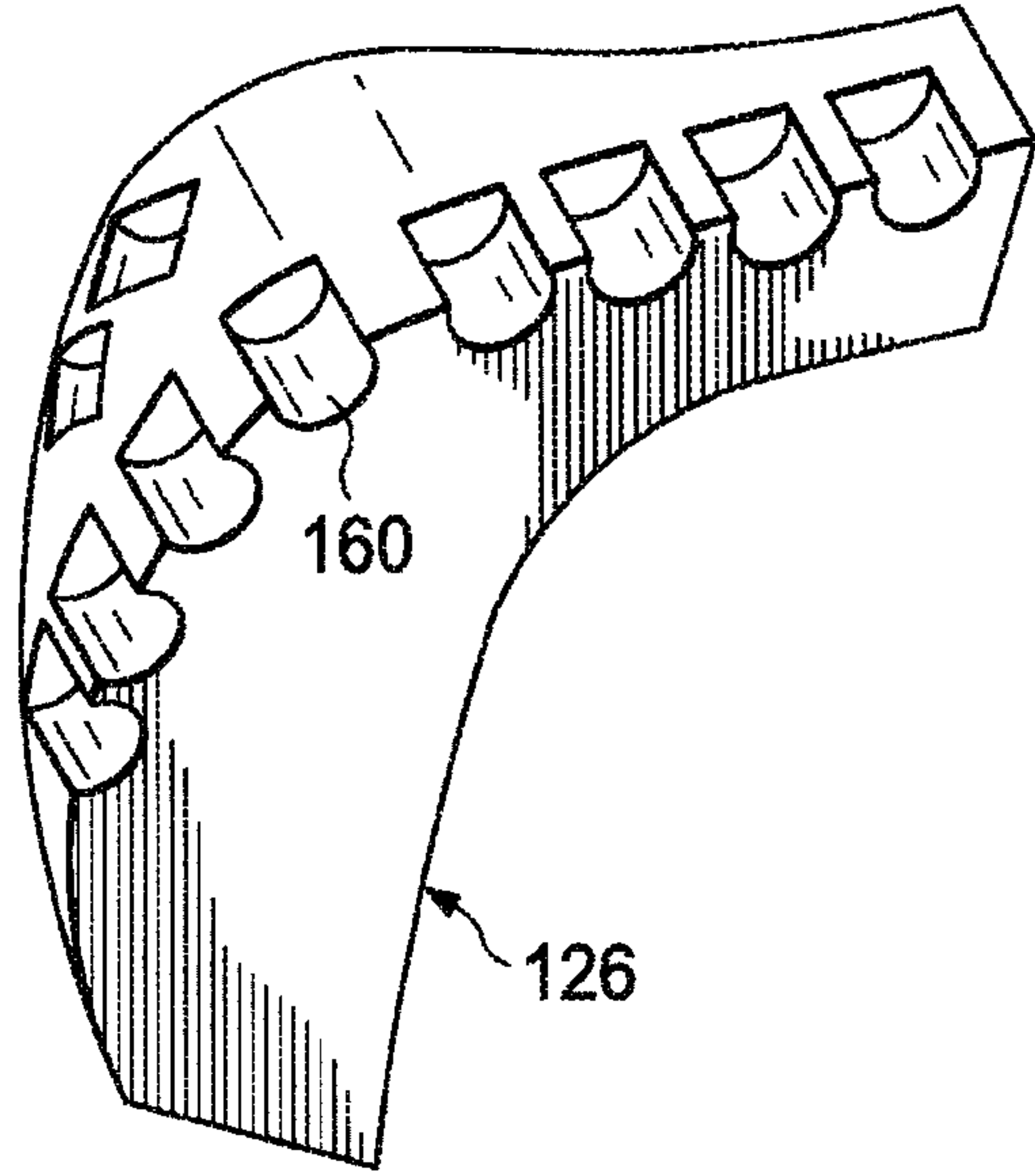


FIG. 3

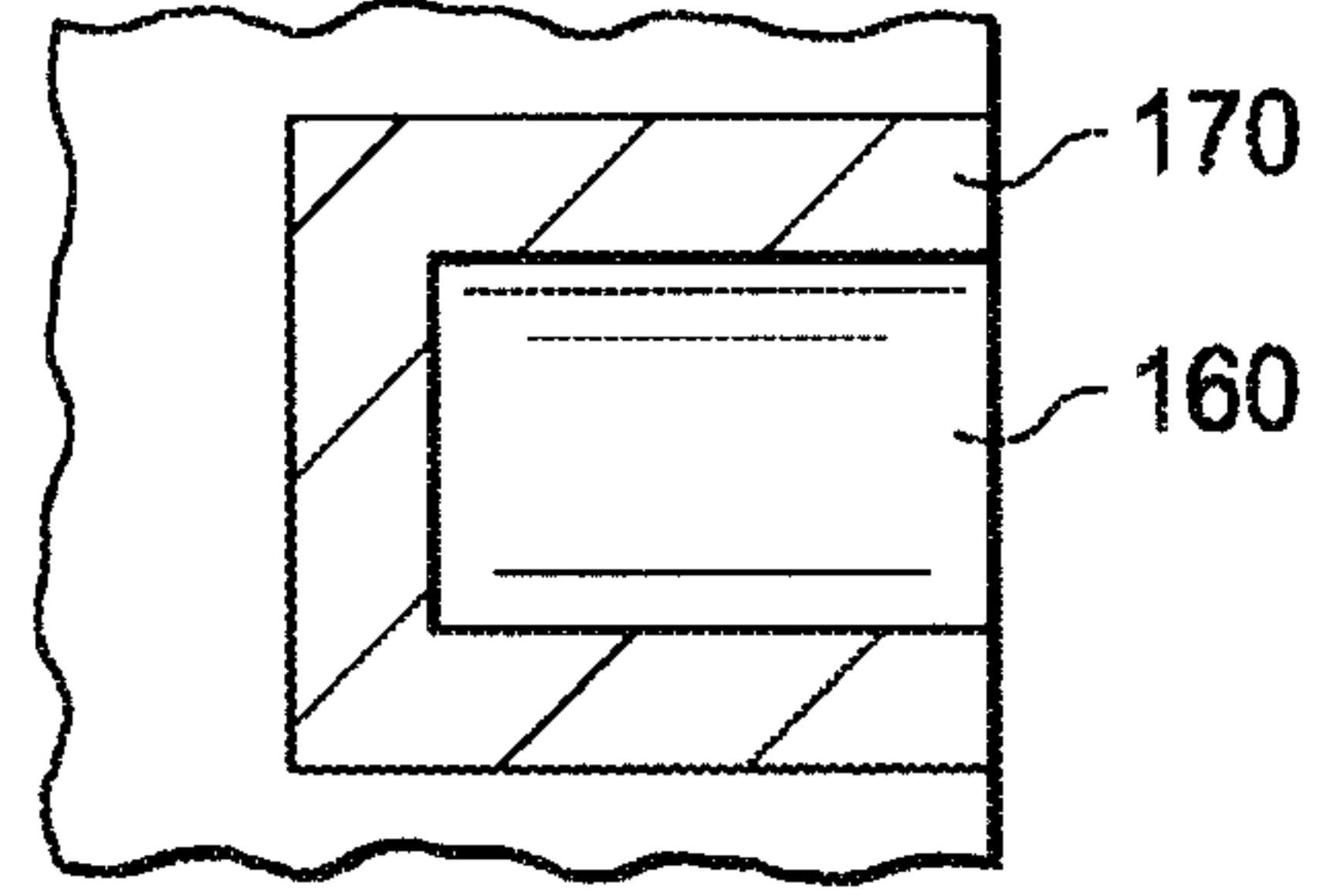


FIG. 4

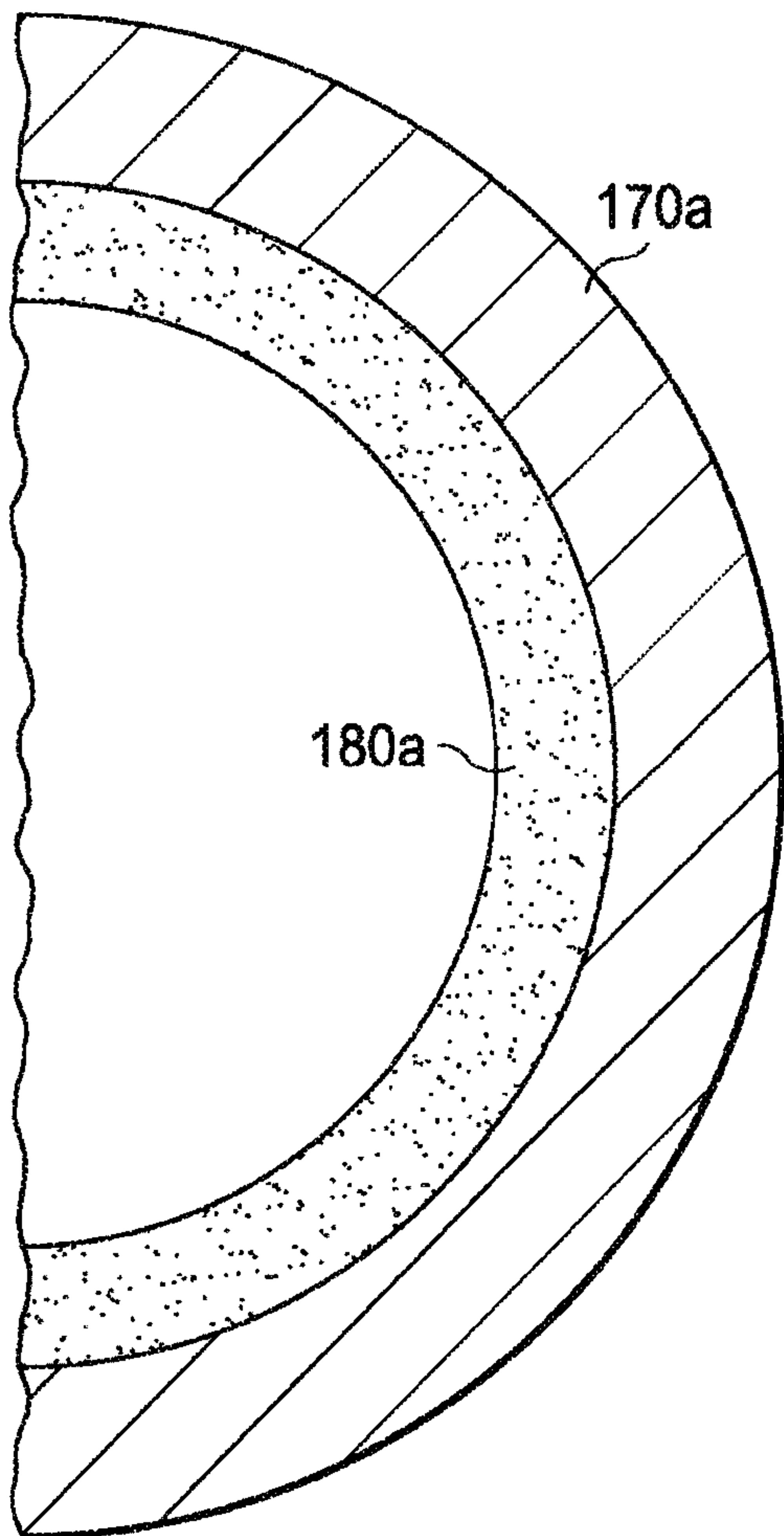


FIG. 5A

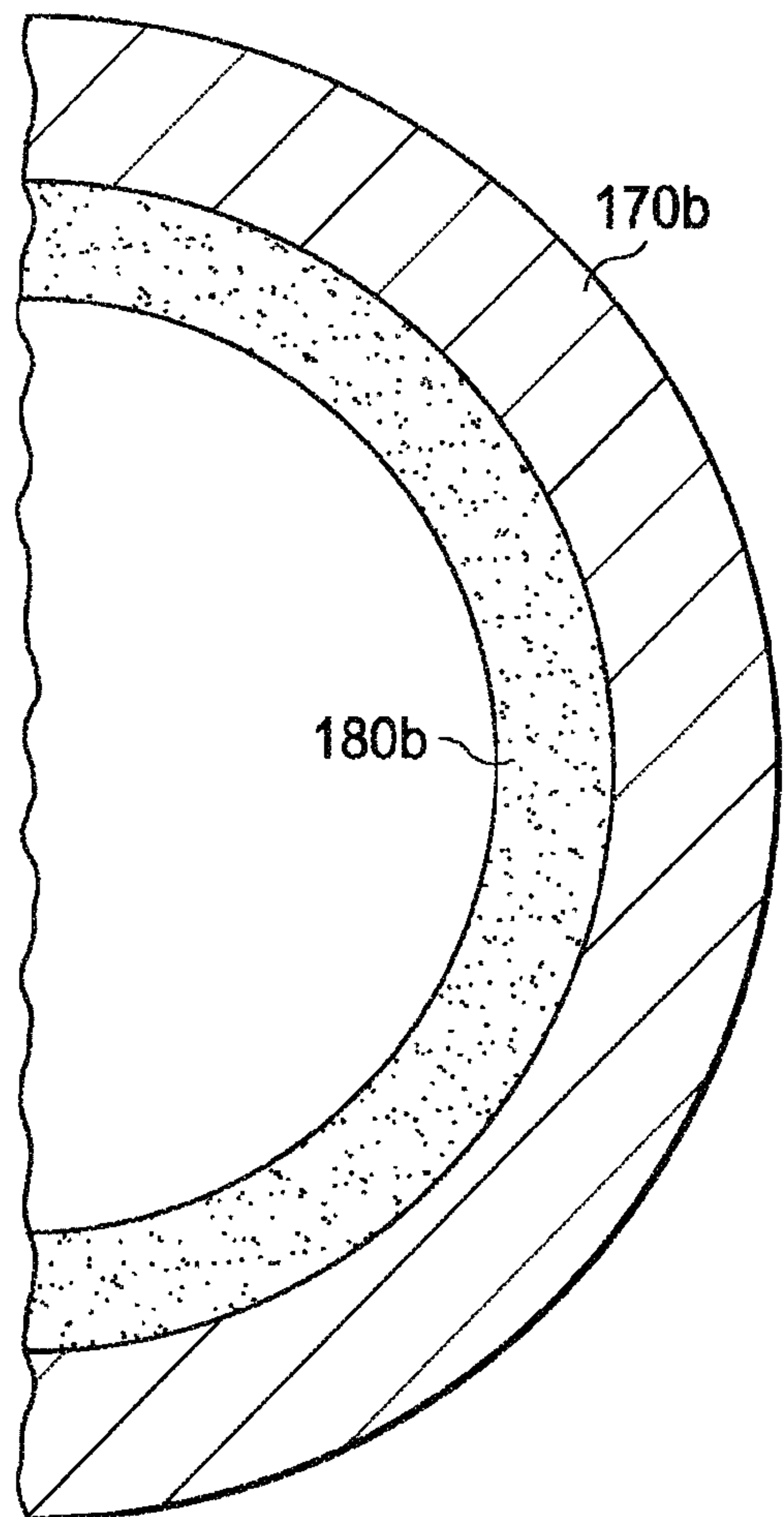


FIG. 5B

4/4

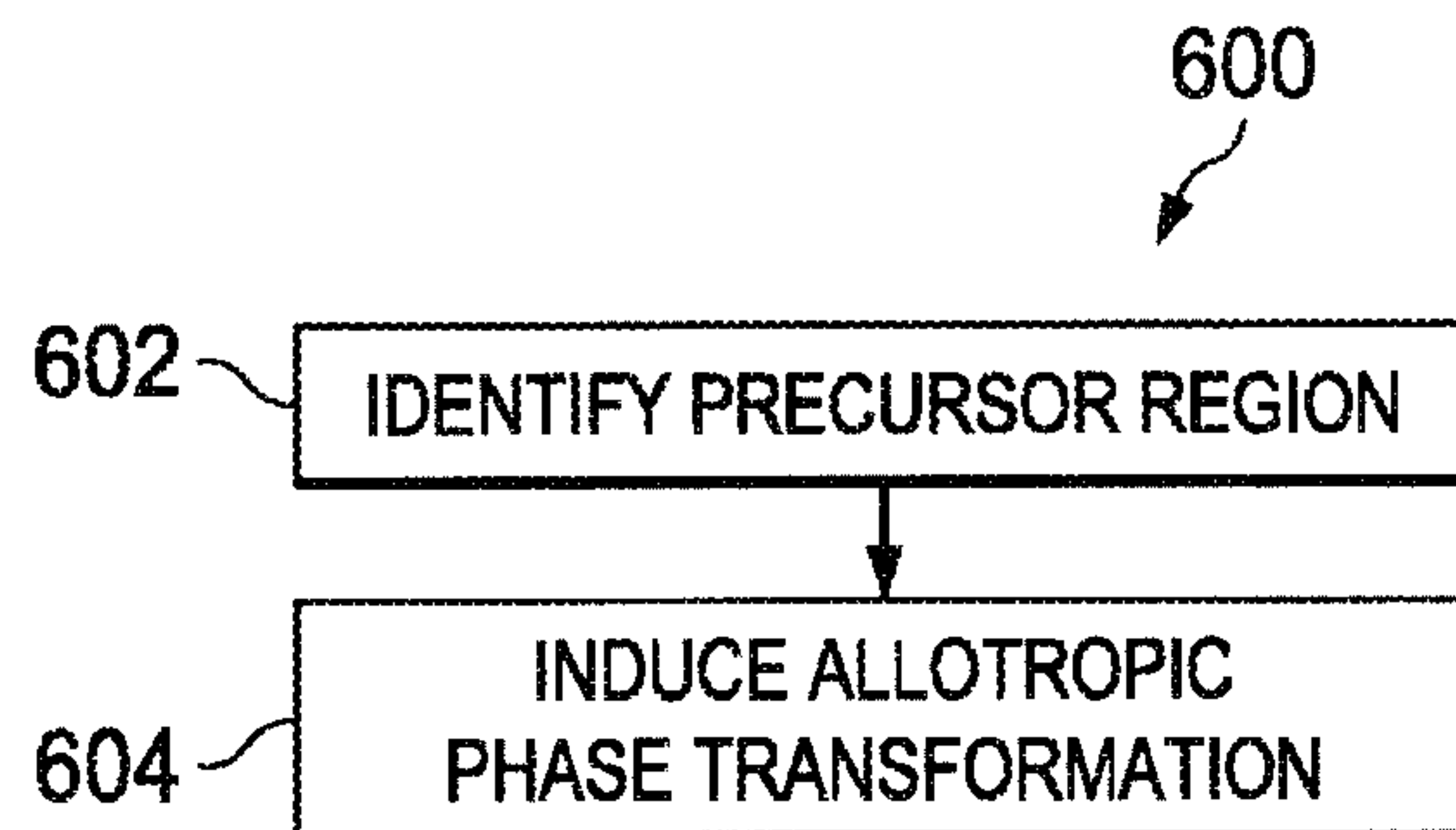


FIG. 6

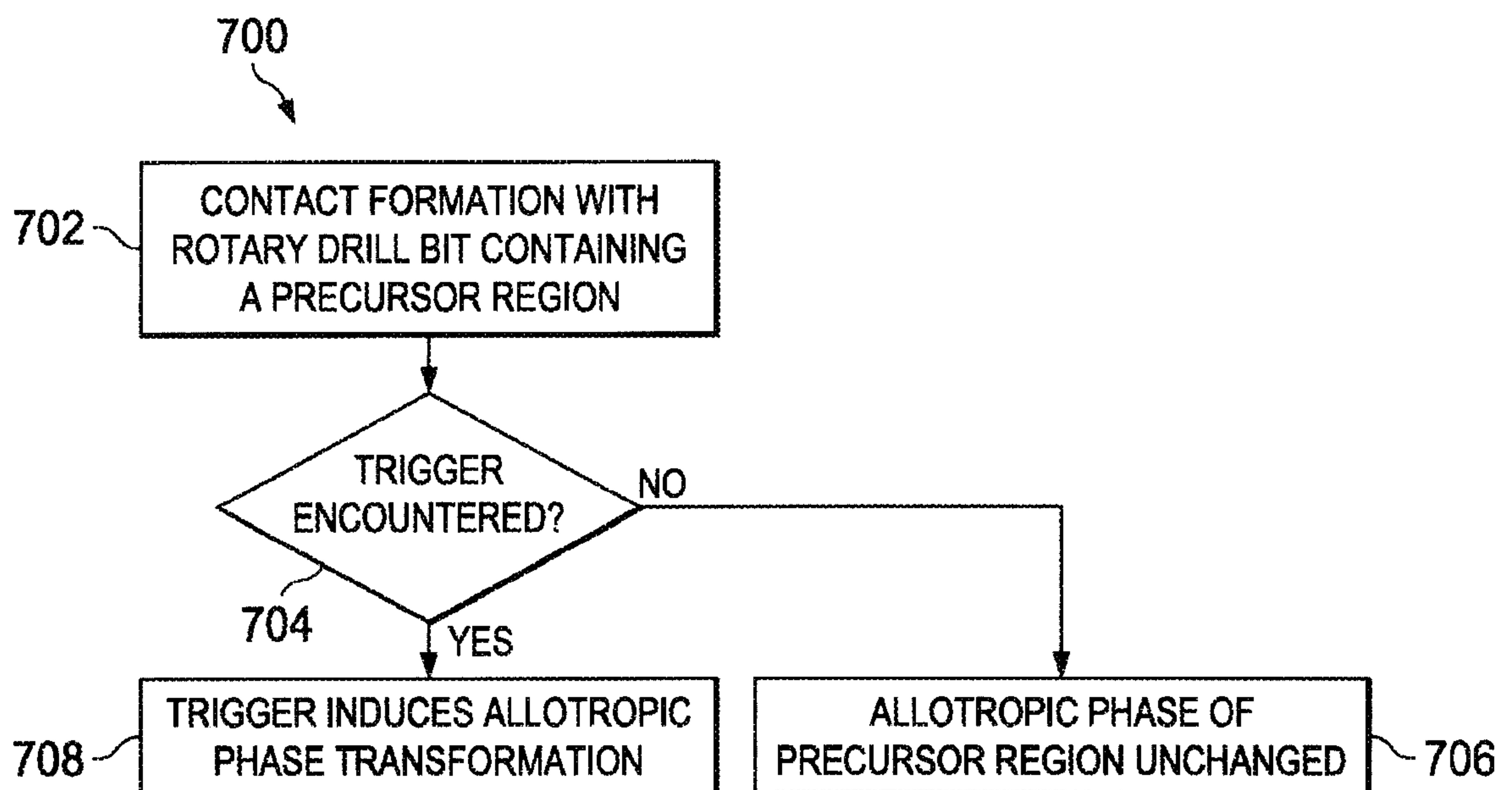


FIG. 7

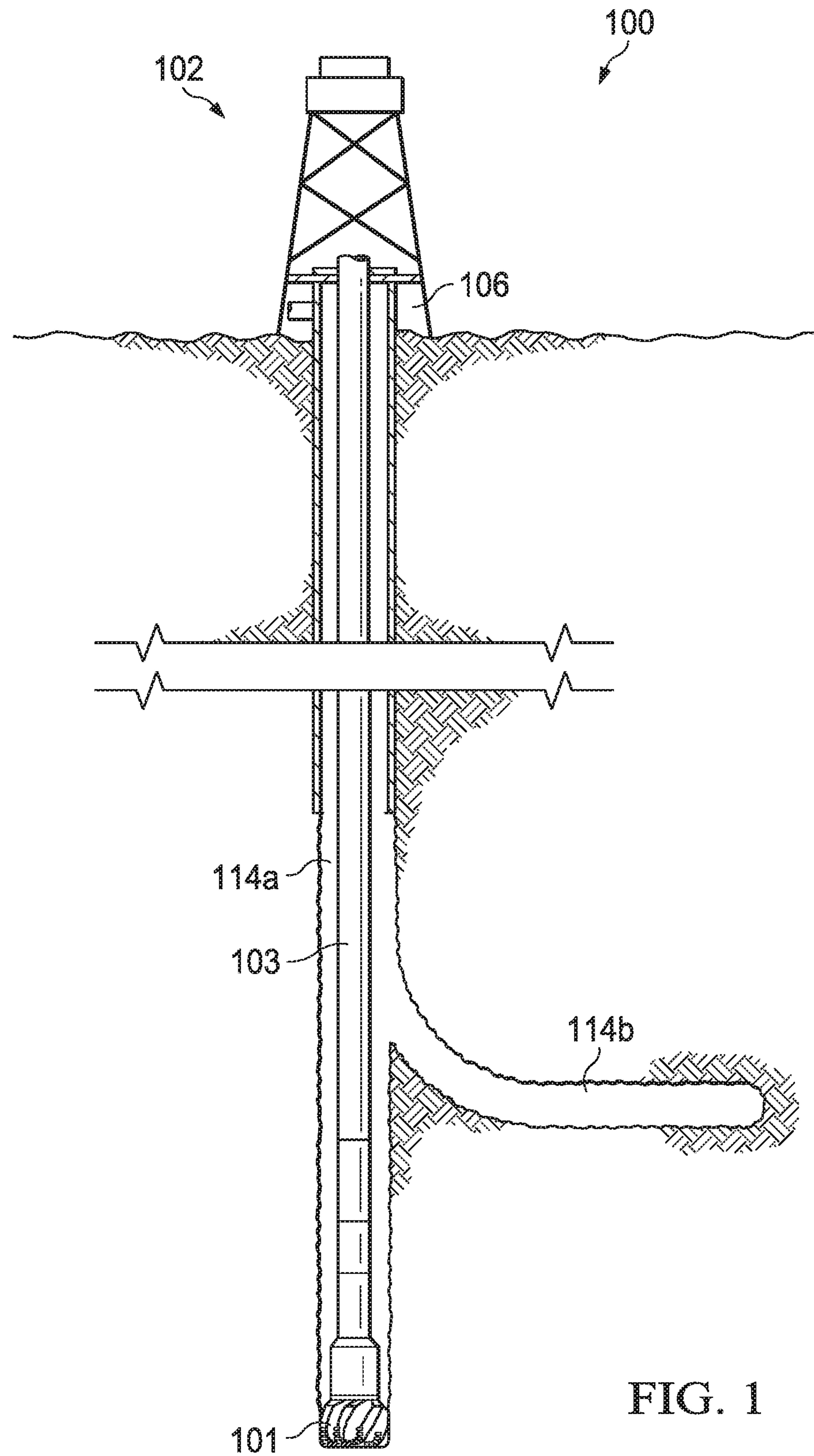


FIG. 1