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(54) NEUTRON-DETECTING APPARATUSES AND METHODS OF FABRICATION

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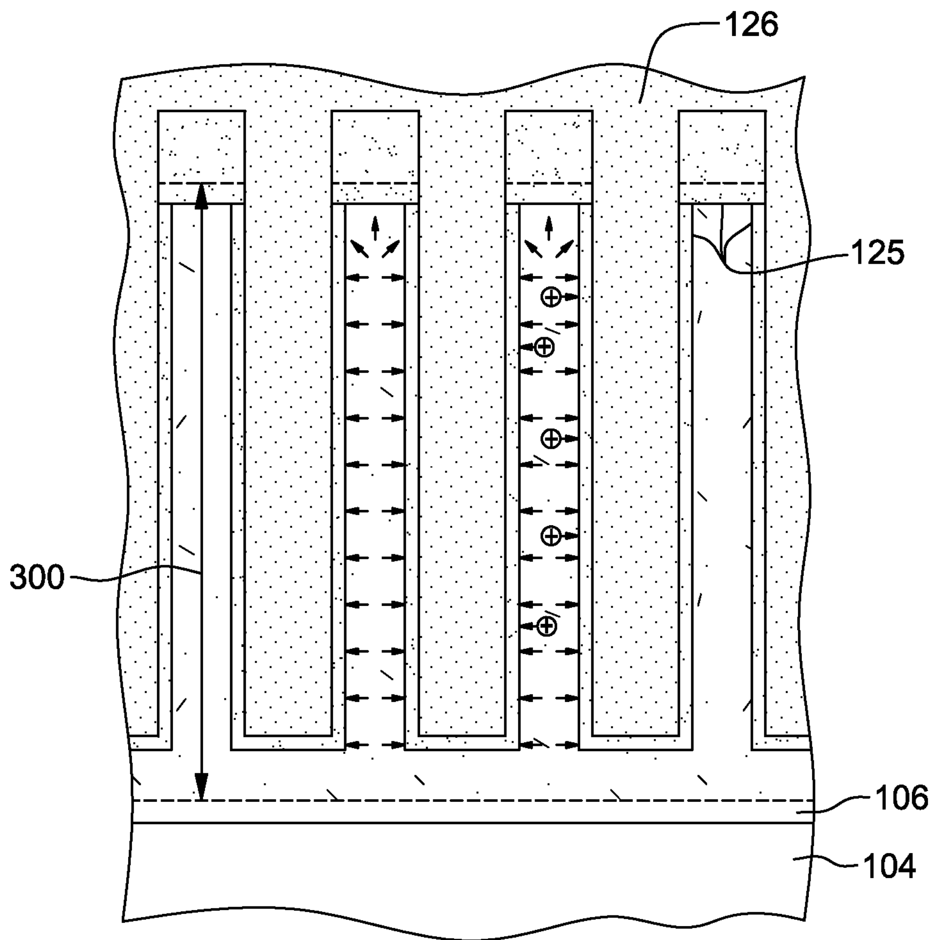
CPC ***G01T 3/08*** (2013.01); ***H01L 31/115*** (2013.01)
USPC **257/429**; 438/56

(57) **ABSTRACT**

Neutron-detecting structures and methods of fabrication are provided which include: a substrate with a plurality of cavities extending into the substrate from a surface; a p-n junction within the substrate and extending, at least in part, in spaced opposing relation to inner cavity walls of the substrate defining the plurality of cavities; and a neutron-responsive material disposed within the plurality of cavities. The neutron-responsive material is responsive to neutrons absorbed for releasing ionization radiation products, and the p-n junction within the substrate spaced in opposing relation to and extending, at least in part, along the inner cavity walls of the substrate reduces leakage current of the neutron-detecting structure.



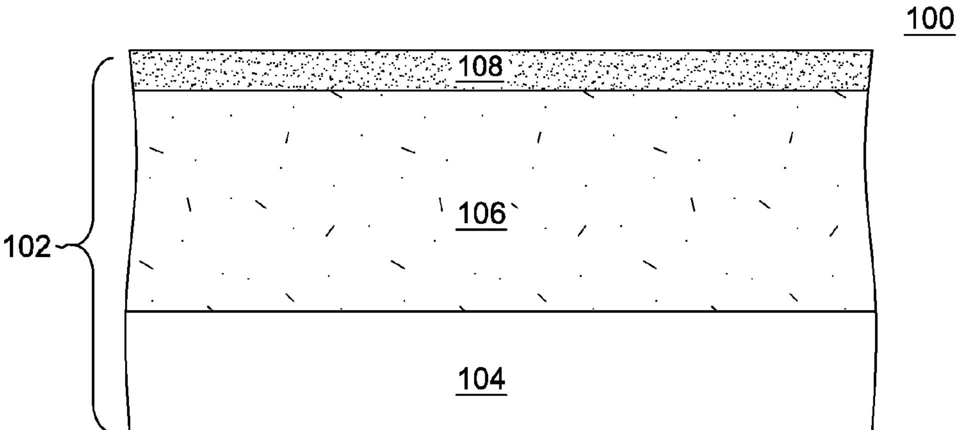


FIG. 1A

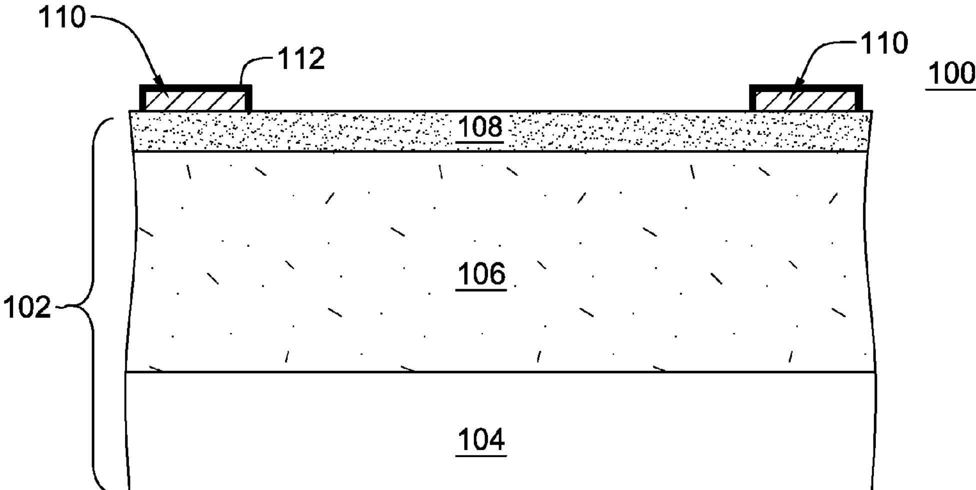


FIG. 1B

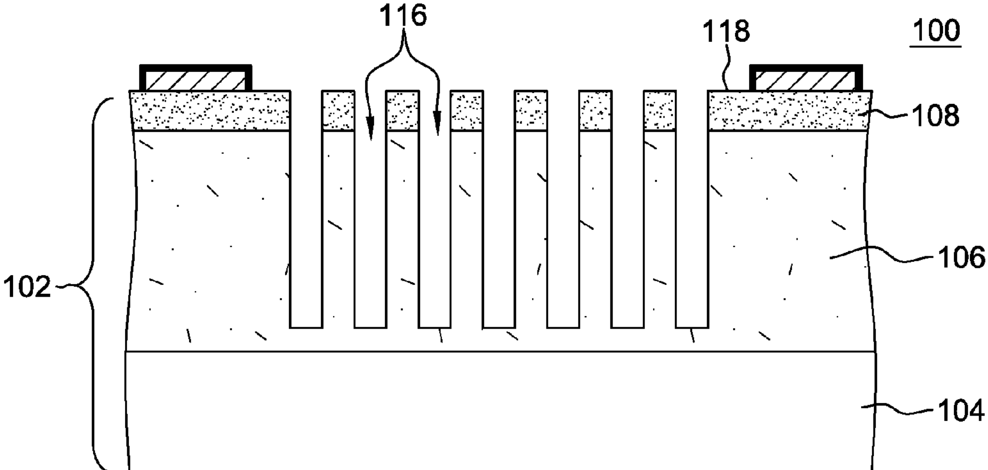


FIG. 1C

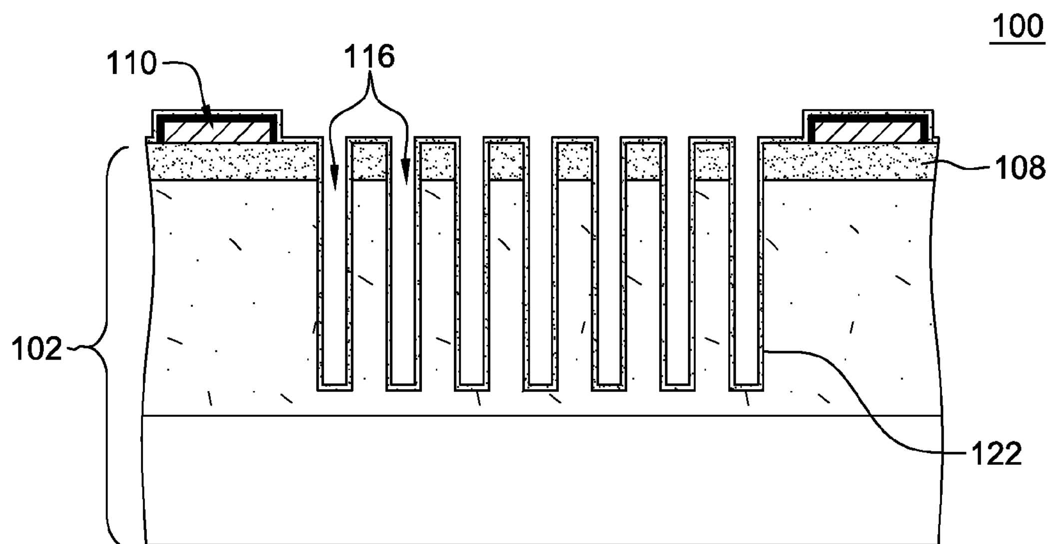


FIG. 1D

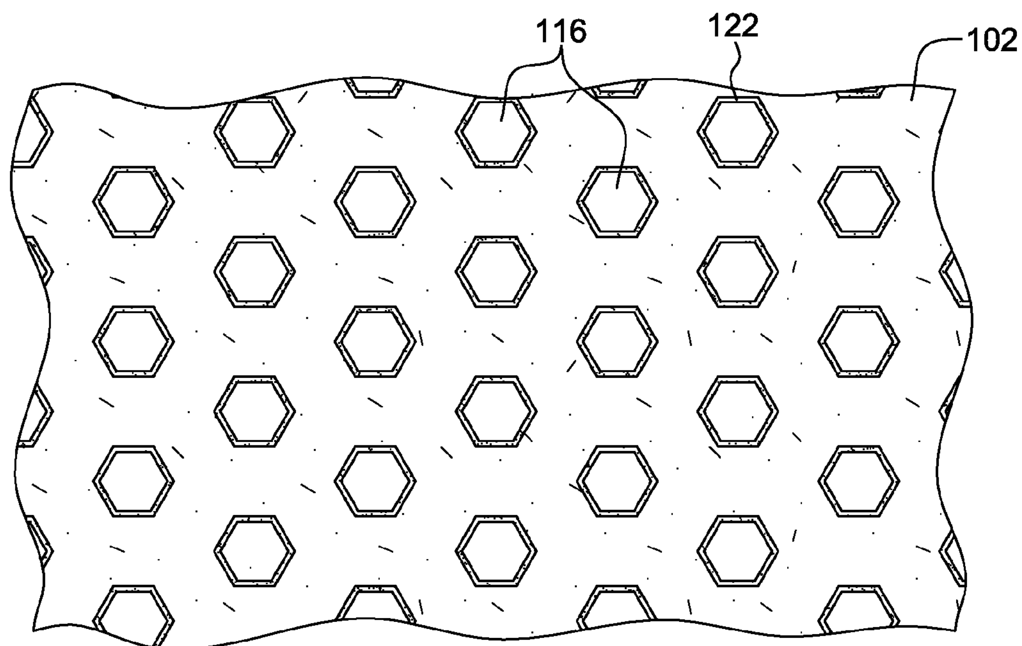


FIG. 1E

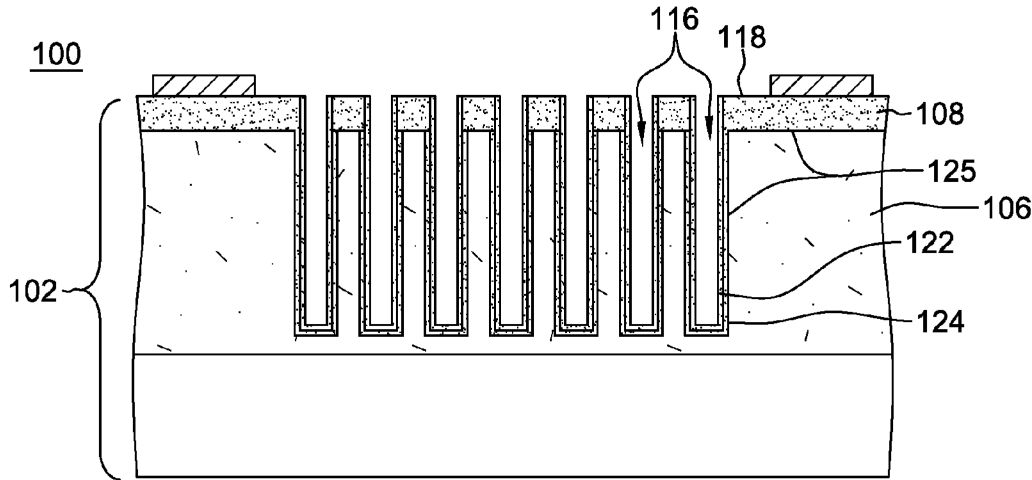


FIG. 1F

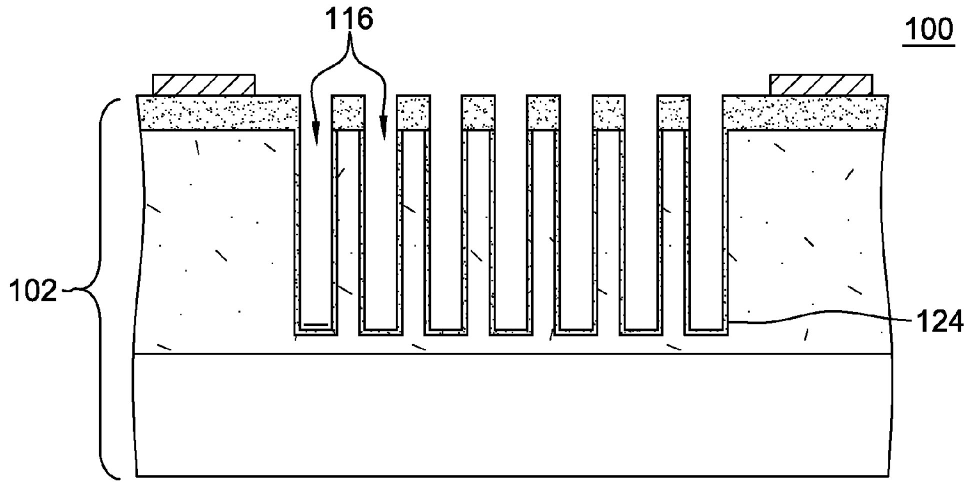


FIG. 1G

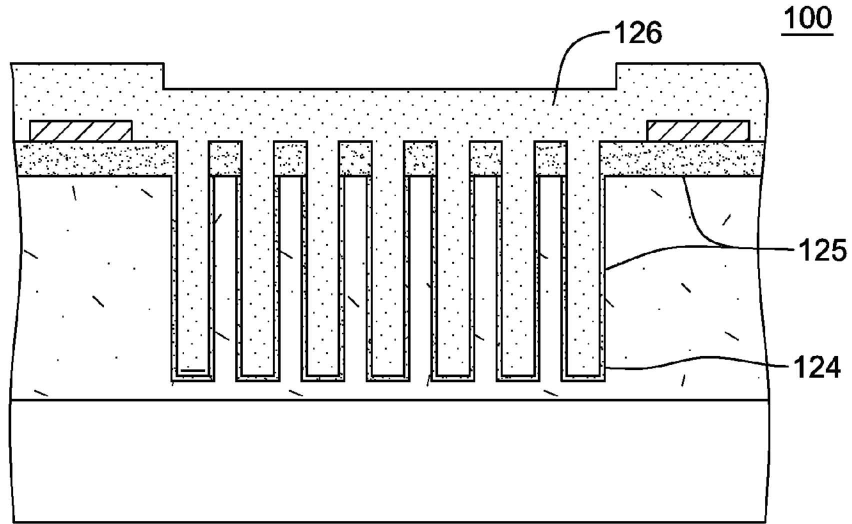


FIG. 1H

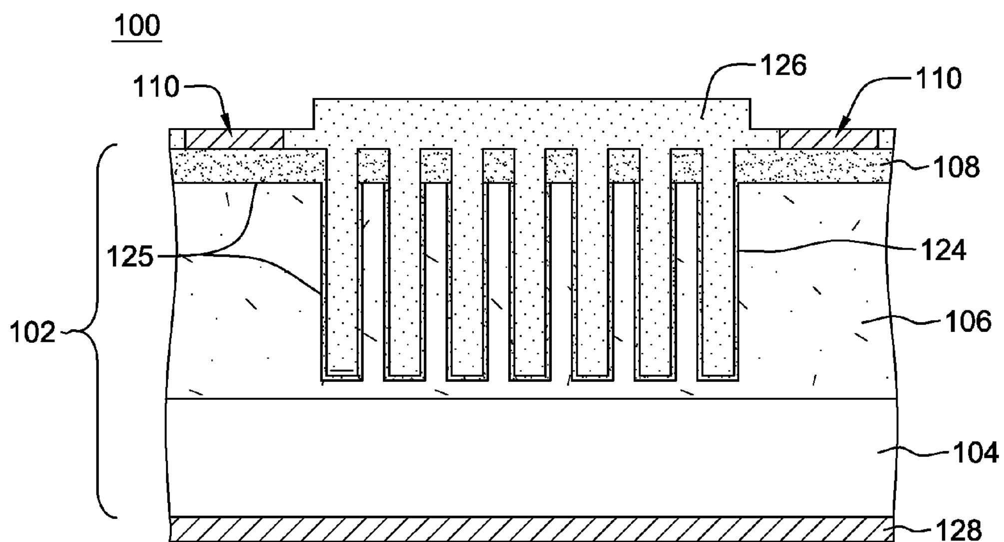


FIG. 1I

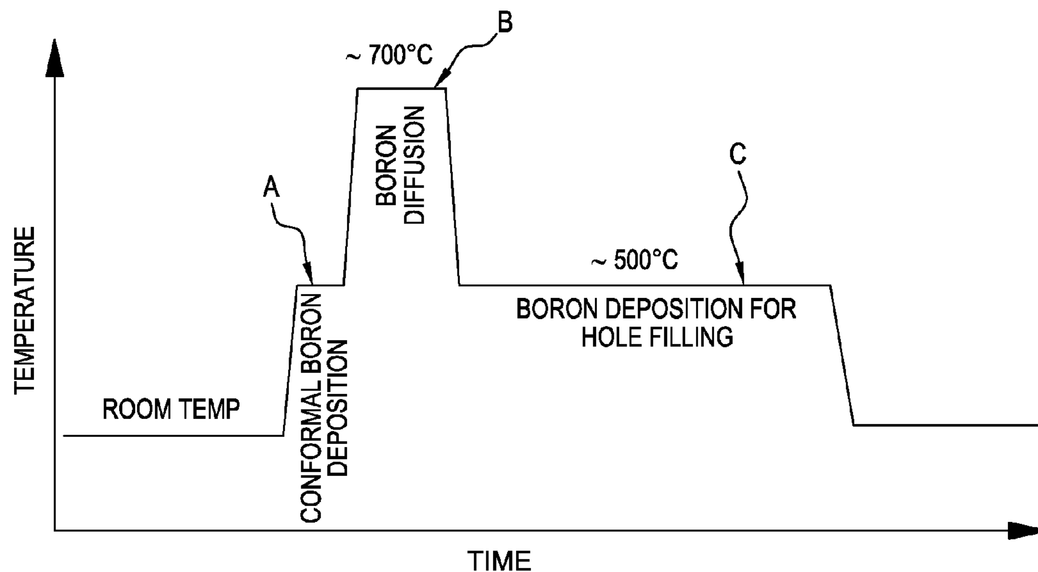


FIG. 2

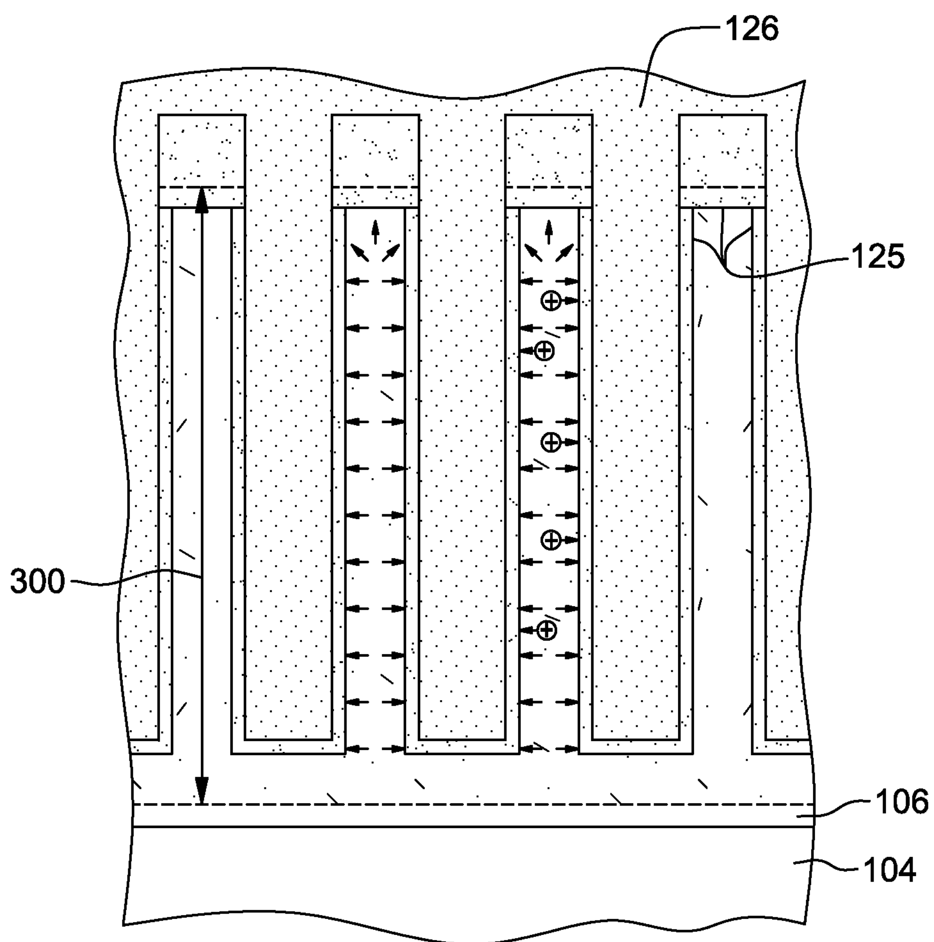


FIG. 3

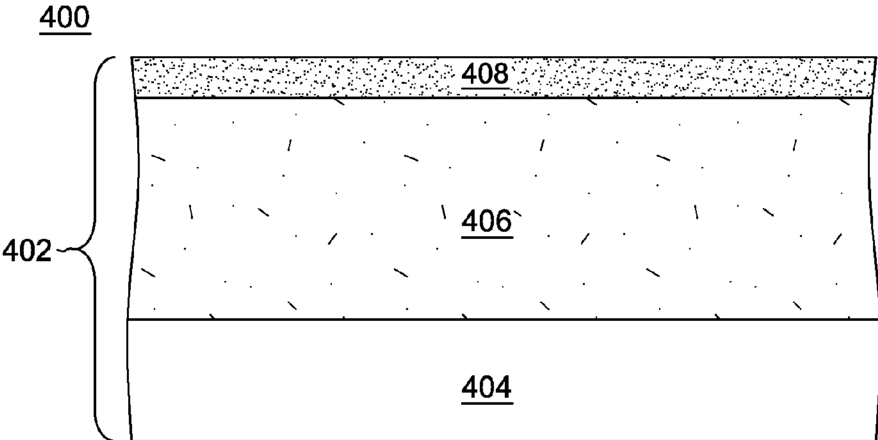


FIG. 4A

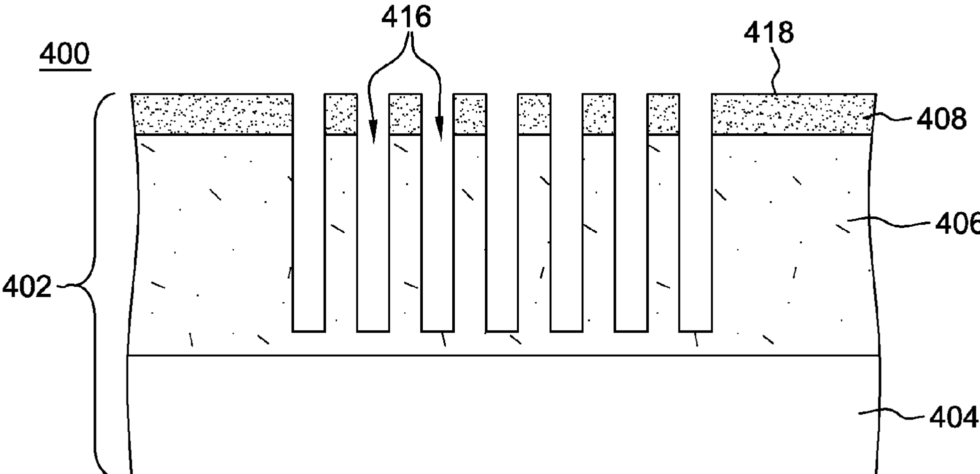


FIG. 4B

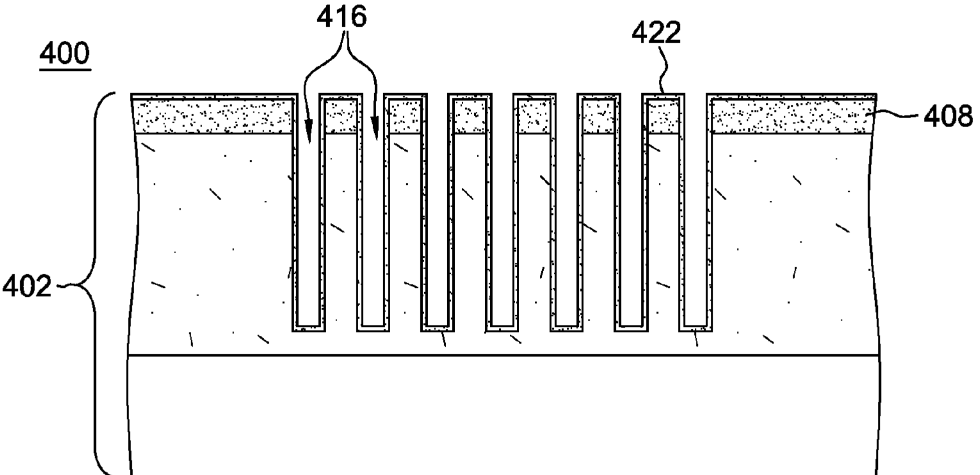


FIG. 4C

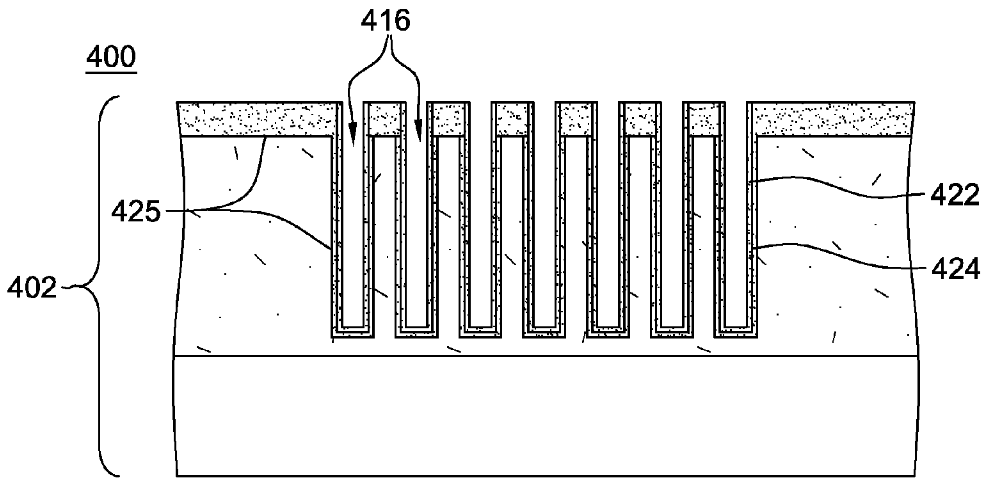


FIG. 4D

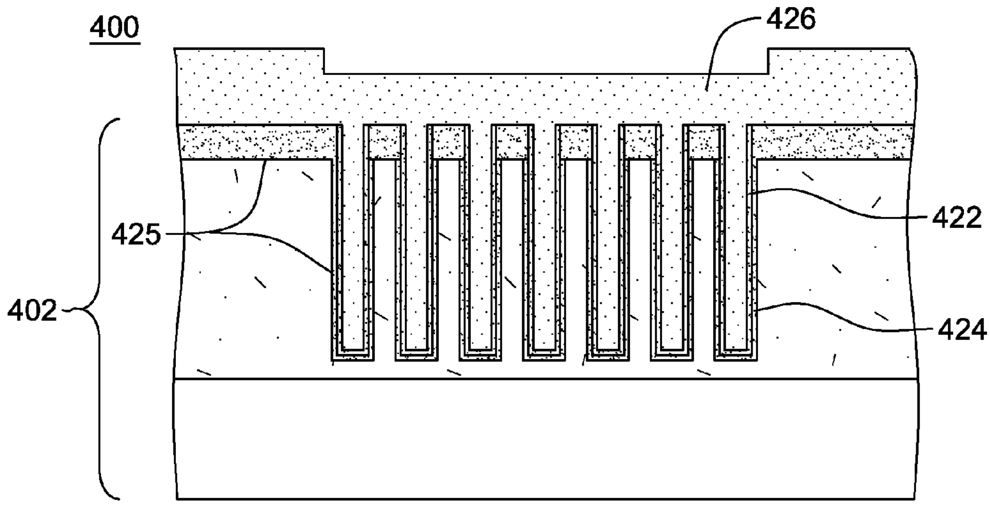


FIG. 4E

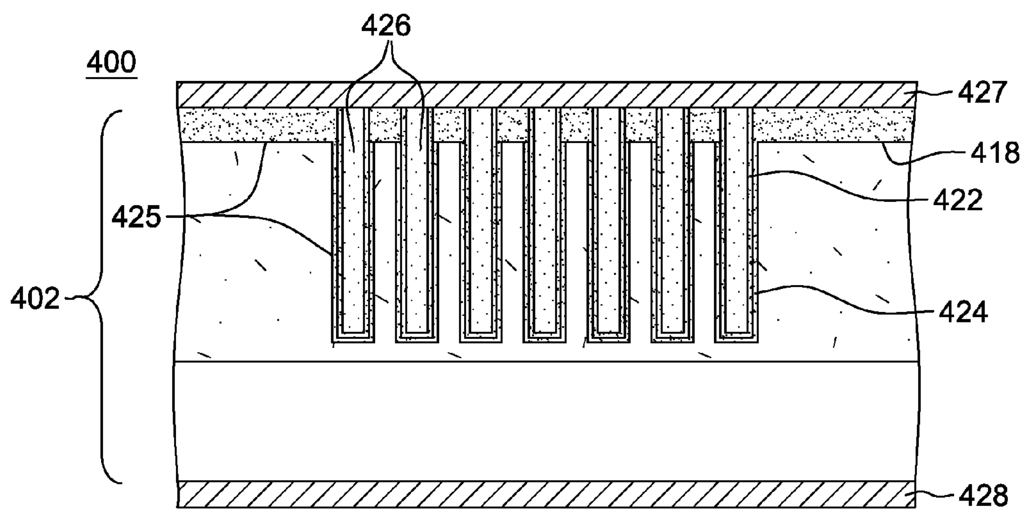


FIG. 4F

NEUTRON-DETECTING APPARATUSES AND METHODS OF FABRICATION

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of U.S. Provisional Patent Application No. 61/723,471, filed Nov. 7, 2012, which is hereby incorporated herein by reference in its entirety.

BACKGROUND

[0002] Efficient solid-state neutron-detectors with large detecting surfaces and low gamma sensitivity are desired for detecting and preventing proliferation of special nuclear materials (SNMs). Unfortunately, available neutron-detectors are limited, for instance, by size, weight, high bias voltage requirements, and/or cost due, for instance, to limited supply of enriched helium (^{3}He) gas, which is currently employed in most neutron-detectors.

[0003] Although a variety of solid-state neutron-detectors have been proposed, existing neutron-detectors often embody a trade-off between neutron-detector efficiency and gamma discrimination, as most neutron sources or reactions are generally accompanied by gamma ray events. For example, an increase in sensitivity of a neutron-detector often results in a concomitant increase in sensitivity of detecting undesired gamma ray events.

[0004] Thus, there remains a need for further neutron-detection approaches, and in particular, a need for a novel, self-powered, robust and efficient solid-state neutron-detector.

BRIEF SUMMARY

[0005] The shortcomings of the prior art are overcome and additional advantages are provided through the provision, in one aspect, of an apparatus which includes: a neutron-detecting structure. The neutron-detecting structure includes, for instance: a substrate including a plurality of cavities extending into the substrate from a surface thereof; a p-n junction within the substrate and extending, at least in part, in spaced opposing relation to inner cavity walls of the substrate defining the plurality of cavities therein; and a neutron-responsive material disposed within the plurality of cavities, the neutron-responsive material being responsive to neutrons absorbed thereby for releasing ionizing radiation reaction products, wherein the p-n junction within the substrate spaced in opposing relation to and extending, at least in part, along the inner cavity walls of the substrate reduces leakage current of the neutron-detecting structure.

[0006] In a further aspect, a method is presented which includes fabricating a neutron-detecting structure, the fabricating including: providing a substrate including a plurality of cavities extending into the substrate from a surface thereof; forming a p-n junction within the substrate and extending, at least in part, in spaced opposing relation to inner cavity walls of the substrate defining the plurality of cavities therein, the p-n junction within the substrate spaced in opposing relation to and extending, at least in part, along the inner cavity walls of the substrate reducing leakage current of the neutron-detecting structure; and providing a neutron-responsive material within the plurality of cavities, the neutron-responsive material being responsive to neutrons absorbed thereby for releasing ionizing radiation reaction products.

[0007] Additional features and advantages are realized through the techniques of the present invention. Other embodiments and aspects of the invention are described in detail herein and are considered a part of the claimed invention.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0008] One or more aspects of the present invention are particularly pointed out and distinctly claimed as examples in the claims at the conclusion of the specification. The foregoing and other objects, features, and advantages of the invention are apparent from the following detailed description taken in conjunction with the accompanying drawings in which:

[0009] FIG. **1**A is a cross-sectional elevational view of one embodiment of a structure obtained during fabrication of a neutron-detecting structure, in accordance with one or more aspects of the present invention;

[0010] FIG. **1**B depicts the structure of FIG. **1**A, after electrical contacts have been provided over a surface thereof, in accordance with one or more aspects of the present invention;

[0011] FIG. **1**C depicts the structure of FIG. **1**B, after etching thereof to provide a plurality of cavities within the substrate, in accordance with one or more aspects of the present invention;

[0012] FIG. **1**D depicts the structure of FIG. **1**C, after provision of a conformal layer of material over the structure, including within the cavities thereof, in accordance with one or more aspects of the present invention;

[0013] FIG. **1**E is a plan-view of one embodiment of the structure of FIG. **1**D, with the plurality of cavities shown arrayed in a honeycomb pattern, and the plurality of cavities being a plurality of hexagonal-cross-sectional-shaped cavities, in accordance with one or more aspects of the present invention;

[0014] FIG. **1**F depicts the structure of FIG. **1**D, after a continuous p-n junction has been formed within the substrate, in accordance with one or more aspects of the present invention;

[0015] FIG. **1**G depicts the structure of FIG. **1**F, after optional removal of the conformal layer of material from the plurality of cavities, in accordance with one or more aspects of the present invention;

[0016] FIG. **1**H depicts the structure of FIG. **1**G, after deposition of neutron-responsive material within the cavities thereof, in accordance with one or more aspects of the present invention;

[0017] FIG. **1**I depicts the structure of FIG. **1**H, after etch-back of the neutron-responsive material and provision of a contact over a second surface structure, in accordance with one or more aspects of the present invention;

[0018] FIG. **2** is a graphical representation of one embodiment of a temperature profile utilized during deposition of the conformal layer of material, formation of the continuous p-n junction, and subsequent deposition of the neutron-responsive material within the cavities, in accordance with one or more aspects of the present invention;

[0019] FIG. **3** is an enlarged depiction of the neutron-detecting structure of FIG. **1**I, showing an enlarged depletion region within the substrate due to the presence of the continuous p-n junction, in accordance with one or more aspects of the present invention;

[0020] FIG. **4**A is a cross-sectional elevational view of another embodiment of a structure obtained during fabrication of neutron-detecting structure, in accordance with one or more aspects of the present invention;

[0021] FIG. **4**B depicts the structure of FIG. **4**A, after etching thereof to provide a plurality of cavities within the substrate, in accordance with one or more aspects of the present invention;

[0022] FIG. **4**C depicts the structure of FIG. **4**B, after deposition of a conformal layer of material over the structure, including within the cavities thereof, in accordance with one or more aspects of the present invention;

[0023] FIG. **4**D depicts the structure of FIG. **4**C, after a continuous p-n junction has been formed within the substrate, in accordance with one or more aspects of the present invention;

[0024] FIG. **4**E depicts the structure of FIG. **4**D, after deposition of neutron-responsive material within the cavities thereof, in accordance with one or more aspects of the present invention; and

[0025] FIG. **4**F depicts the structure of FIG. **4**E, after contacts have been provided over opposite surfaces thereof for electrical connection to the neutron-detecting structure, in accordance with one or more aspects of the present invention.

DETAILED DESCRIPTION

[0026] Aspects of the present invention and certain features, advantages, and details thereof, are explained more fully below with reference to the non-limiting embodiments illustrated in the accompanying drawings. Descriptions of well-known materials, fabrication tools, processing techniques, etc., are omitted so as to not unnecessarily obscure the invention in detail. It should be understood, however, that the detailed description and the specific examples, while indicating embodiments of the invention, are given by way of illustration only, and are not by way of limitation. Various substitutions, modifications, additions and/or arrangements within the spirit and/or scope of the underlying inventive concepts will be apparent to those skilled in the art from this disclosure. Further, note that in making reference below to the drawings (which are not drawn to scale for ease of understanding) the same reference numbers used throughout different figures designate the same or similar components.

[0027] Neutrons, being charge-less particles, tend not to ionize. However, their collisions with other nuclei often result in energetic ionization reaction products, which in turn generate electron-hole pairs (EHPs), which may be separated either by a built-in electric field or by an external bias voltage. These electron-hole pairs can be efficiently detected by solid-state semiconductor junctions, resulting in such neutron-detectors being generally used in a range of applications, including, for example, civilian and defense applications. Unfortunately, available neutron-detectors are often limited, for instance, by size, weight and high bias voltage requirements. Furthermore, the limited supply of enriched helium (^3He), which is currently employed in many neutron-detectors, results in significant cost constraints and performance limitations.

[0028] The realization of a chip-scale, self-powered or very low power-consuming, efficient solid-state neutron-detector utilizing matured silicon processing technology, such as disclosed herein, will provide significant cost and volume benefits, as well as allow wafer-level detector integration with, for instance, charge preamplifier and/or neutron-event counting electronics.

[0029] To summarize, as an enhancement to existing detectors, disclosed herein is an apparatus which includes a neutron-detecting structure comprising, for instance, a substrate including a plurality of cavities extending into the substrate from a surface thereof; a continuous p-n junction within the substrate and extending, at least in part, in spaced opposing relation to inner cavity walls of the substrate defining the plurality of cavities; and a neutron-responsive material disposed within the plurality of cavities. The neutron-responsive material is responsive to neutrons absorbed thereby for releasing ionizing radiation reaction products detected by the detector, and the continuous p-n junction within the substrate spaced in opposing relation to and extending, at least in part, along the inner cavity walls of the substrate advantageously reduces leakage current of the neutron-detecting structure.

[0030] In one specific embodiment, the p-n junction is formed by depositing a conformal layer of p-type dopant material at a first temperature, and annealing the conformal p-type dopant material at a second temperature, which is higher than the first temperature. Annealing at the second temperature facilitates forming the continuous p-n junction extending within the substrate in spaced opposing relation to the inner cavity walls of the substrate. In one example, the second temperature is at least about 100° C. to 300° C. higher than the first temperature. Note that the conformal layer of p-type dopant material may comprise a conformal layer of neutron-responsive material deposited within the plurality of cavities. This conformal layer of neutron-responsive material may be, for instance, a p-type dopant such as, for example, enriched boron (^{10}B) or a compound of enriched boron, for instance, boron carbide ($^{10}B_4C$) or boron nitride (^{10}BN).

[0031] As noted, in one embodiment, the p-n junction formed within the substrate is a continuous p-n junction and is disposed, in part, parallel to the surface of the substrate from which the plurality of cavities extend into the substrate, as well as in spaced opposing relation to the inner cavity walls of the substrate. In one specific example, the continuous p-n junction may be opposing and spaced from the surface of the substrate a greater distance than the continuous p-n junction is spaced from the inner cavity walls of the substrate. Advantageously, in operation, the substrate will include a depletion region which, due to the presence of the continuous p-n junction, extends within the substrate to at least a depth of the plurality of cavities within the substrate.

[0032] In one implementation, one or more of the plurality of cavities within the substrate is, at least in part, a hexagonal-cross-sectional-shaped cavity. For instance, the plurality of cavities may be arrayed, at least in part, in a honeycomb pattern within the substrate, which advantageously assists with mechanical stability to the resultant solid-state neutron-detecting structure.

[0033] In one embodiment, the apparatus may further include multiple neutron-detecting structures or modules such as disclosed herein, which may be advantageously electrically coupled in series. Note that the solid-state, neutron-detecting structures disclosed herein are designed or configured to operate at minimal, or even zero, bias voltage.

[0034] By way of explanation, certain embodiments of a neutron-detecting structure and methods of fabrication thereof, in accordance with one or more aspects of the present invention, are described below with reference to FIGS. **1A-1I**.

[0035] FIG. **1**A illustrates a structure **100** attained during fabrication of a solid-state, neutron-detecting structure, in accordance with one or more embodiments of the present invention. In the depicted embodiment, structure **100** includes a substrate **102**, which as one example, may be a bulk semiconductor material, such as, for example, a bulk silicon wafer in a crystalline structure with any suitable crystallographic orientation. Suitable crystallographic orientations may include, for example, (100), (110) and (111) orientation. Although not critical to the invention, in one example, substrate **102** may have a planar (100) crystallographic surface orientation (referred to as "(100)" surface).

[0036] In the depicted example, substrate **102** has been implanted with n-type dopants to create a high-conducting n^+ region **104**, as well as an n^- region **106**. Note that, n-type dopant refers to the addition of impurities to, for instance, intrinsic (undoped) substrate material, which contribute more electrons to the intrinsic material, and may include (for instance) phosphorus, arsenic or antimony. In one example, n^+ region **104** and n_- region **106** of the substrate may be formed using conventional ion implantation or diffusion processing techniques. The n^+ region **104** may have a thickness in the range of about 100 to 1,000 microns, and n^- region may have a thickness of about 40 μm to 50 μm. Additionally, the resistivity of n^- region may be in the range of about 10-50 Ω-cm. One skilled in art will understand that n^+ region **104** of substrate **102** is heavily-doped with n-type dopants as compared to n^- region **106** of the substrate.

[0037] Substrate **102** of structure **100** further includes a highly conducting p^+ region **108** disposed over n^- region **106**. This p^+ region **108** may be obtained by addition of impurities to, for instance, intrinsic (undoped) substrate material to create deficiencies of valence electrons in the intrinsic material. Examples of appropriate p-type dopant include boron, aluminum, gallium, or indium. In one example, p^+ region **108** of substrate **102** is formed using conventional ion implantation or diffusion processing techniques and may have thickness of about 1 to 3 μm.

[0038] FIG. **1**B depicts structure **100** after provision of conductive contacts **110** over p^+ region **108** of the substrate. Conductive contacts **110** may be selectively patterned as desired over p^+ region **108**, and facilitate subsequent electrical connection to the resultant neutron-detecting structure or module. Note that conductive contact material may be any of a variety of conductive materials, such as tungsten, titanium, copper, aluminum, molybdenum etc. Although not depicted, one skilled in the art will recognize that a silicide may optionally be formed by providing a layer of polysilicon over p^+ region of the substrate, prior to the deposition of the conductive contact material. The layer of polysilicon reacts chemically with the silicon of p^+ region **108** to form the silicide over p^+ region **108** of the substrate. In one example, the layer of polysilicon deposited over p^+ region **108**, may have thickness in the range of about 30-50 nm, while the conductive contact material deposited over the layer of polysilicon may have thickness in the range of about 50 to 100 nm. Note that the layer of polysilicon, if provided, also acts as a buffer layer in preventing the diffusion of conductive contact material into the underlying p^+ region, during subsequent device processing.

[0039] A protective layer **112** may be provided over the conductive contacts **110**, using, for instance, any conventional deposition processes, such as atomic layer deposition (ALD), chemical-vapor deposition (CVD), physical vapor deposition (PVD) or the like. In one example, protective layer **112** may be or include an oxide material, for instance, silicon dioxide, and may be provided to protect the conductive contacts structure, during subsequent fabrication processing.

[0040] As depicted in FIG. **1**C, a portion of substrate **102** is patterned with a plurality of cavities **116**, which extend (in the depicted example) from a surface **118** of substrate **102** into at least a portion of n^- region **106** of substrate **102**. Note that deep reactive ion etching (DRIE) or plasma etching process may be employed to pattern substrate **102** with a plurality of high-aspect-ratio cavities **116**. In another example, an anisotropic dry etching process may alternatively (or also) be employed to pattern the cavities. In one specific example, deep reactive ion etching is performed using fluorine-based chemistry, which may involve process gases such as nitrogen trifluoride (NF_3), sulfur hexafluoride (SF_6), tetrafluoromethane (CF_4), trffluoromethane (CH_3F), difluoromethane (CH_2F_2), fluoromethane (CH_3F), octafluorcyclobutane (C_4F_8), hexafluoro-1,3-butadiene (C_4F_6) in inert gaseous medium such as argon (Ar).

[0041] In one specific example, one or more, or even each, cavity of the plurality of cavities **116** is configured with a hexagonal-cross-sectional shape. By way of example, the hexagonal-cross-sectional-shaped cavities may have a diameter in the range of about 1-3 μm and a depth of about 40-50 μm, extending into the substrate, with adjacent cavities being separated, for example, by about 1 to 1.3 μm of substrate.

[0042] As illustrated in FIG. **1**D, a conformal layer **122** of material (in this example, p-type dopant material) may next be deposited. Conformal layer **122**, which overlies structure **100**, including within the plurality of cavities **116**, may be deposited using a modified chemical vapor deposition (CVD) process. For instance, the CVD process may be modified by varying parameters such as, temperature and pressure, to obtain the desired conformal layer. Note that the conformal layer **122** of p-type dopant material may be deposited at a first temperature, for instance, in the range of about 450° C. to 550° C.

[0043] Conformal layer **122** may be or include, in one embodiment, a conformal layer of neutron-responsive material, which may be or include the p-type dopant. Examples of appropriate p-type dopants include boron, aluminum, gallium, or indium, being deposited. In one specific example, the conformal layer of neutron-responsive material may include at least one of enriched boron (^{10}B) or a compound of enriched boron such as, for example, boron carbide ($^{10}B_4C$, $^{10}B_5C$) or boron nitride (^{10}BN).

[0044] In one specific example, conformal layer **122** may be deposited using a conventional CVD process, by employing enriched boron precursors such as, for example, diborane (B_2H_6), deca-borane ($B_{10}H_{14}$) or other metal organoborane precursors such as, triethylborane $(C_2H_5)_3B$ or trimethylborane $(CH_3)_3B$, at about 500° C. Note that the enriched boron precursors employed may contain more than 95% of enriched boron (^{10}B) isotope. In one embodiment, thickness of the conformal layer along the inner walls of the cavities **116** may be, for example, in the range of about 10 to 20 nm. Note that the conductive contacts **110**, discussed above in connection with FIG. **1**B, remain unaffected by this processing, due to the low temperature conditions employed. One skilled in the art will also note that any residual layer of polysilicon that may have been deposited over p^+ region **108** of substrate **102**, during the formation of conductive contacts **110**, may be converted to silicide, under these low temperature deposition

conditions, by reacting chemically with any residual underlying silicon of p^+ region **108**, thereby further improving the quality of the conductive contacts **110**.

[0045] By way of example, FIG. **1**E is a partial cross-sectional plan view of one embodiment of a neutron-detection structure, such as described above in connection with FIGS. **1**A-**1**D. As illustrated, in one or more embodiments, the plurality of cavities **116** of the neutron-detecting structure or module may be arrayed in a honeycomb pattern within the substrate **112**. For instance, one or all the plurality of cavities may have a hexagonal-cross-sectional shape, with the resultant honeycomb pattern providing the solid-state, neutron-detecting structure with enhanced mechanical rigidity compared with other cavity configurations and layouts.

[0046] As illustrated in FIG. **1**F, conformal layer **122** (of p-type dopant material) is subjected to a controlled annealing process to provide a p-region **124** within substrate **102** along the inner walls of the plurality of cavities **116**. The result is to form a continuous p-n junction **125** within substrate **102** at the interface between p^+ region **108**, n^- region **106**, and between p-region **124** and n^- region **106**. Note that the controlled annealing to produce p-region **124** is performed at a second temperature, higher than the first temperature. This higher temperature anneal results in a portion of the p-type dopant from conformal layer **122** diffusing into the underlying n^- region **106** of the substrate, thereby facilitating formation of the continuous p-n junction **125** within the substrate.

[0047] Note that the second, annealing temperature is at least about 100° C. to 300° C. higher than the first temperature at which conformal layer **122** is deposited. As one specific example, continuous p-n junction **125** may be formed within substrate **102**, by increasing the process temperature from 500° C. to about 700° C., for 10 to 30 minutes, to promote diffusion of p-type dopant (such as, for example, boron) from the conformal layer into the underlying n^- region **106** of the substrate. The thickness of p-region **124** may be controlled by controlling process parameters such as, for instance, temperature and time, at which the annealing is performed. In one example, the thickness of p-region **124** may be in the range of about 20 nm to 200 nm. In the embodiment illustrated, continuous p-n junction **125** is, in part, in spaced opposing relation to surface **118** of the substrate, and is, in part, in spaced opposing relation to the inner walls of substrate **102** defining cavities **116**. As illustrated, continuous p-n junction **125** is spaced from surface **118** of the substrate **102** a greater distance than it is spaced from the inner cavity walls of the substrate. In one embodiment, conformal layer **122** may be polished back from upper surface of structure **100** using, for instance, chemical mechanical polishing, stopping on contacts **110** and p^+ region **108** of the substrate. Note that the conformal layer of p-type dopant material disposed within cavities **116** would remain unaffected, during this etch-back polishing processing. After this polish-back, neutron-responsive material may be disposed within the cavities **116** of structure **100**, in a manner such as described below.

[0048] FIG. **1**G depicts an alternate embodiment, wherein conformal layer **122** is removed from structure **100** after formation of p-region **124** within the substrate. By way of example, conformal layer **122** may be selectively removed using, for instance, a plasma formed from, for example, a mixture of oxygen (O_2) and a fluorine-containing gas, such as, carbon tetrafluoride (CF_4). In FIGS. **1**H & **1**I depicted below, it is assumed that the conformal layer **122** has been removed prior to provision of the neutron-responsive material within the plurality of cavities. As noted above, in an alternate implementation, the conformal layer **122** may remain within the plurality of cavities without affecting operation of the resultant neutron-detecting structure, particularly where the conformal layer comprises the above-noted enriched boron (^{10}B) or compounds of enriched boron.

[0049] FIG. **1**H illustrates structure **100** after a neutron-responsive material **126** has been provided within cavities **116**. In one embodiment, neutron-responsive material **126** may be or include at least one of enriched boron (^{10}B) or a compound of enriched boron such as, for example, boron carbide ($^{10}B_4C$, $^{10}B_5C$) or boron nitride (^{10}BN). In one specific example, neutron-responsive material **126** may be deposited using a low-temperature, high-pressure CVD process, by employing enriched boron precursors such as, for example, diborane (B_2H_6), deca-borane ($B_{10}H_{14}$) or other metal organoborane precursors such as, triethylborane $(C_2H_5)_3B$ or trimethylborane $(CH_3)_3B$, at about 500° C. Note that the enriched boron precursors employed herein may contain, for instance, more than 95% of enriched boron (^{10}B) isotope. Note also that the neutron-responsive material (for instance, enriched boron or a compound of enriched boron) advantageously facilitates absorbing thermal neutrons and converting the absorbed neutrons into energetic charged particles, thereby allowing for the detection operation of the solid-state, neutron-detecting structure. In one example, enriched boron or a compound of enriched boron has a high thermal absorption coefficient, for instance, of about 3840 barn, making enriched-boron an efficient neutron-responsive material. Additionally, large absorption lengths of neutrons in boron-rich neutron-detectors, and short escape lengths of energetic-charged particles, further enhance the efficiency of boron-rich neutron-detecting structures.

[0050] Note further that, in an alternate embodiment, neutron-responsive material **126** may comprise other materials capable of performing the neutron-detection function. For instance, the material may alternatively be or include a hydrogen-rich aromatic polymer material such as, for example, poly(p-xylylene) polymer (also referred to herein as parylene) or polystyrene.

[0051] Note that the low-temperature, high-pressure chemical vapor deposition process employed to deposit the neutron-responsive material within cavities **116** advantageously facilitates filling the cavities without defects, and thereby, enhances the efficiency of the resultant neutron-detecting structure. Although the modified deposition conditions accomplish an efficient filling of the cavities, one skilled in the art will note that with high-aspect-ratio depositions, a tear-shaped void may be created within one or more of the cavities. In the event of such an occurrence, a small portion of the neutron-responsive material may be etched using any suitable etching processing, for example, reactive ion etching, while protecting the remaining neutron-responsive material within the cavities, for instance, using a photoresist material, and subsequently be re-deposited until the tear-shaped void is removed. Alternatively, one or more small voids within the cavities may remain in place without significantly affecting operation of the resultant neutron-detecting structure.

[0052] As depicted in FIG. **1**I, the neutron-responsive material **126** may be partially removed to expose conductive contacts **110** on the one side of the structure, and a conductive contact **128** may be provided on the opposite side, for instance, the under-side of the structure. In one embodiment,

conductive contact **128** is provided over highly conducting n^+ region **104** of substrate **102**. Note that conductive contact **128** may be formed of any of a variety of conductive materials, such as tungsten, titanium, copper, aluminum, molybdenum etc. Although not depicted, one skilled in the art will recognize that a silicide may also be formed, for instance, by providing a layer of polysilicon over the exposed surface of n^+ region **104**, prior to the deposition of the conductive contact. The layer of polysilicon reacts chemically with the silicon of n^+ region **104** to form silicide over the n^+ region. In one example, the layer of polysilicon deposited over n^+ region **104** may have thickness in the range of about 30-50 nm, while conductive contact **128** deposited over the layer of polysilicon may have thickness in the range of about 50 to 100 nm. Note that, if provided, the polysilicon will also act as a buffer layer in preventing the diffusion of conductive contact **128** into the underlying n^+ region during subsequent fabrication processing.

[0053] By way of further example, FIG. **2** is a graphical representation of a temperature profile which may be employed during device fabrication, including deposition of a conformal layer of material, formation of the continuous p-n junction and a subsequent deposition of the neutron-responsive material within the cavities, in accordance with one or more aspects of the present invention. As discussed, in one embodiment, a conformal layer of p-type dopant material may be deposited (A), employing a low-temperature, high-pressure chemical-vapor deposition (CVD) process. As one specific example, a p-type neutron-responsive material such as, boron may be deposited within the cavities at about 500° C. The conformal layer may be subjected to an annealing process (B) by increasing the process temperature by about 100° C. to 300° C. for a short time duration, for example, about 10 mins to 30 mins, resulting in diffusion of a portion of p-type material (for example, boron) into the underlying substrate, thereby forming the portion of the p-n junction within the substrate extending, at least in part, in spaced opposing relation to the inner cavity walls of the substrate. The neutron-responsive material may subsequently be deposited (C) within the cavities, during which the temperature of the CVD process is lowered to about 500° C. and the pressure is increased by about 100 ton, as compared to a conventional CVD process. Note that these modified process parameters efficiently improve the deposition rate of the neutron-responsive material within the cavities. In one specific example, the deposition rate at which the neutron-responsive material is deposited may be in the range of about 1.5 to 2 μm/hr. Note that efficiency of the resultant neutron-detecting structure may depend on the particular process parameters, such as temperature and pressure, used during chemical-vapor deposition of the neutron-responsive material.

[0054] The efficiency of neutron-detecting structures may be further enhance by patterning a silicon substrate having (110) crystallographic orientation, with a plurality of cavities using, for example, highly-selective, conventional wet-etching processes. In such an example, the inner cavity walls may have (111) and (100) crystallographic orientations, and a controlled, low-pressure CVD process may be employed to deposit the neutron-responsive material.

[0055] As an operational example, FIG. **3** depicts an enlarged partial view of the structure of FIG. **1**I. In this example, an increased depletion region **300** (i.e., compared with the depletion region of a conventional neutron-detector) is formed within the substrate due to the presence of the continuous p-n junction **125** wrapping around the cavities. Note that continuous p-n junction **125** may act as a passivation layer along the inner walls of cavities **116**, as well as provide a built-in electric field in the radial direction which completely depletes the adjoining inner walls of the substrate without any external biasing voltage, thereby increasing the area of the depletion region within the substrate. Passivation of the substrate using continuous p-n junction **125**, and the increased size of depletion region **300** within the substrate, advantageously facilitate reducing leakage current and capacitance of the resultant neutron-detecting structure, and thereby facilitate producing devices with large collection surface areas, and improved charge collection efficiency, with minimal external bias voltage required. As noted, the continuous p-n junction may even operate at zero bias voltage.

[0056] Those skilled in the art will note that the reverse leakage current I_o of the detector depends on diffusion current and recombination current. The diffusion current is given by:

$$I_{od} = qA\frac{D_p n_i^2}{L_p N_D},$$

where I_{od} is the diffusion part of the reverse leakage current, A is the detector area, D_p and L_p are the diffusion coefficient and diffusion length of the n-type silicon respectively, n_i is the intrinsic carrier concentration for intrinsic silicon, and N_D is the doping concentration of n-type silicon respectively.

[0057] The recombination current is given by:

$$I_{or} = \frac{qn_{iAW}}{2\tau_o},$$

where W is the depletion layer width, and τ_o is approximately an average of electron and hole lifetime and depends on the location of the recombination center in the bandgap.

[0058] As noted, the continuous p-n junction disclosed herein advantageously facilitates in preventing the n^- region from being exposed (except at the edge of the neutron-detector), thereby resulting in a residual leakage current principally due to any recombination current. Note also that the n^- region remains unaffected further reducing the diffusion current, and the depletion region extends along the inner walls of the plurality of cavities, thereby further reducing the leakage current.

[0059] By way of further example, FIGS. **4**A-**4**F depicts another embodiment of a neutron-detecting structure and methods of fabrication thereof, in accordance with one or more aspects of the present invention.

[0060] FIG. **4**A illustrates a structure **400** attained during fabrication of a solid-state neutron-detecting structure, in accordance with one or more aspects of the present invention. In this embodiment, structure **400** includes a substrate **402**, which may be a bulk semiconductor material, such as, for example, a bulk silicon wafer in a crystalline structure with any suitable crystallographic orientation. Suitable crystallographic orientations may include, for example, (100), (110) and (111) orientation. Although not critical to the invention, in one example, substrate **402** may have a planar (100) crystallographic surface orientation (referred to as “(100)” surface).

[0061] Substrate **402** has been implanted with n-type dopants to create a high-conducting n^+ region **404**, as well as an n^- region **406**. Note that, n-type dopant refers to the addition of impurities to, for instance, intrinsic (undoped) substrate material, which contribute more electrons to the intrinsic material, and may include (for instance) phosphorus, arsenic or antimony. In one example, n^+ region **404** and n^- region **406** of the substrate may be formed using conventional ion implantation or diffusion processing techniques and the n^+ region **404** may have a thickness in the range of about 1 to 3, and n^- region may have a thickness of about 40 μm to 50 μm. Additionally, the resistivity of n^- region may be in the range of about 10-50 Ω-cm. One skilled in art will understand that the n^+ region **404** of substrate **402** is heavily-doped with n-type dopants as compared to n^- region **406** of the substrate.

[0062] Substrate **402** of structure **400** further includes a high-conducting p^+ region **408** disposed over n^- region **406**. This p^+ region **408** may be obtained by addition of impurities to, for instance, intrinsic (undoped) substrate material to create deficiencies of valence electrons in the intrinsic material. Examples of appropriate p-type dopant may include boron, aluminum, gallium, or indium. In one example, p^+ region **408** of substrate **402** is formed using conventional ion implantation or diffusion processing techniques and may have thickness of about 1 to 3 μm.

[0063] As depicted in FIG. **4**B, a portion of substrate **402** may be patterned with a plurality of cavities **416**, which extend (in the depicted example) from a surface **418** of substrate **402** into at least a portion of n^- region **406** of substrate **402**. Note that a deep reactive ion etching (DRIE) or plasma etching may be employed to pattern substrate **402** with a plurality of high-aspect-ratio cavities **416**. In another example, an anisotropic dry etching process may alternatively (or also) be employed to pattern the cavities. In one specific example, deep reactive ion etching is performed using fluorine-based chemistry, which may involve process gases such as nitrogen trifluoride (NF_3), sulfur hexafluoride (SF_6), tetrafluoromethane (CF_4), trifluoromethane (CH_3F), difluoromethane (CH_2F_2), fluoromethane (CH_3F), octafluorcyclobutane (C_4F_8), hexafluoro-1,3-butadiene (C_4F_6) in inert gaseous medium such as argon (Ar).

[0064] In one specific example, one or more, or even each cavity of the plurality of cavities **416** is configured with a hexagonal-cross-sectional shape. By way of example, the hexagonal-cross-sectional-shaped cavities may have a diameter in the range of about 1-3 μm and a depth of about 40-50 μm, extending into the substrate, with adjacent cavities being separated, for example, by about 1 to 1.3 μm of substrate.

[0065] As illustrated in FIG. **4**C, a conformal layer **422** of material may next be deposited. Conformal layer **422**, which overlies structure **400**, including within the plurality of cavities **416**, may be deposited using a modified chemical vapor deposition (CVD) process. For instance, the CVD process may be modified by varying parameters such as temperature and pressure, to obtain the desired conformal layer. Note that the conformal layer **422** (e.g., of a p-type dopant material) may be deposited at a first temperature, for instance, in the range of about 450° C. to 550° C. Conformal layer **422** may be or include, in one embodiment, a conformal layer of neutron-responsive material, which may be or include the p-type dopant. Examples of appropriate p-type dopant include boron, aluminum, gallium, or indium. In one specific example, the conformal layer of neutron-responsive material may include at least one of enriched boron (^{10}B) or a compound of enriched boron such as, for example, boron carbide ($^{10}B_4C$, $^{10}B_5C$) or boron nitride (^{10}BN).

[0066] In one specific example, conformal layer **422** may be deposited using a conventional CVD process, by employing enriched boron precursors such as, for example, diborane (B_2H_6), deca-borane ($B_{10}H_{14}$) or other metal organoborane precursors such as, triethylborane $(C_2H_5)_3B$ or trimethylborane $(CH_3)_3B$, at about 500° C. Note that the enriched boron precursors employed may contain more than 95% of enriched boron (^{10}B) isotope. In one embodiment, thickness of the conformal layer along the inner walls of cavities **416** may be, for example, in the range of about 10 to 20 nm.

[0067] As illustrated in FIG. **4**D, conformal layer **422** (of p-type dopant material) is subjected to a controlled annealing process to provide a p-region **424** within substrate **402** along the inner walls of the plurality of cavities **416**. The result is to form a continuous p-n junction **425** within substrate **402** at the interface, between p^+ region **408** and n^- region **406**, and between p-region **424** and n^- region **406**. Note that the controlled annealing to produce p-region **424** is performed at a second temperature, higher than the first temperature. This higher temperature anneal results in a portion of the p-type dopant from conformal layer **422** diffusing into underlying n^- region **406** of the substrate, thereby facilitating formation of the continuous p-n junction **425** within the substrate.

[0068] Note that the second, annealing temperature is at least about 100° C. to 300° C. higher than the first temperature at which conformal layer **422** is deposited. As a specific example, a continuous p-n junction **425** may be formed within substrate **402**, by increasing temperature from 500° C. to about 700° C., for about 10 mins to 30 mins, to promote diffusion of p-type dopant (such as, for example, boron) from the conformal layer into the underlying n^- region **406** of the substrate. The thickness of p-region **424** may be controlled by controlling process parameters such as, for instance, temperature and time, at which the annealing is performed. In one example, the thickness of p-region **424** may be in the range of about 20 nm to 200 nm. As illustrated, continuous p-n junction **425** is, in part, in a spaced opposing relation to surface **418** of the substrate, and is, in part, in spaced opposing relation to the inner walls of substrate **402** defining cavities **416**. In the embodiment illustrated, continuous p-n junction **425** is spaced from surface **418** of substrate **402** a greater distance than it is spaced from the inner cavity walls of the substrate. In one embodiment, conformal layer **422** may be polished back from upper surfaces of structure **400** using, for instance, chemical mechanical polishing, stopping on p^+ region **408** of the substrate. Note that the conformal layer of p-type material disposed within cavities **416** remains unaffected, during this etch-back polishing process.

[0069] FIG. **4**E illustrates structure **400** after a neutron-responsive material **426** has been provided within cavities **416**. In one embodiment, neutron-responsive material **426** may be or include at least one of enriched boron (^{10}B) or a compound of enriched boron such as, for example, boron carbide ($^{10}B_4C$, $^{10}B_5C$) or boron nitride (^{10}BN). In one specific example, neutron-responsive material **426** may be deposited using a low-temperature, high-pressure CVD process, by employing enriched boron precursors such as, for example, diborane (B_2H_6), deca-borane ($B_{10}H_{14}$) or other metal organoborane precursors such as, triethylborane $(C_2H_5)_3B$ or trimethylborane $(CH_3)_3B$, at about 500° C. Note that the enriched boron precursors employed herein may contain, for instance, more than 95% of enriched boron (^{10}B)

isotope. Note also that the neutron-responsive material (for instance, enriched boron or a compound of enriched boron) advantageously facilitates absorbing thermal neutrons and converting the absorbed neutrons into energetic charged particles, thereby allowing for the detection operation of the solid-state, neutron-detecting structure.

[0070] Note further that, in an alternate embodiment, neutron-responsive material **426** may comprise other materials capable of performing the neutron-detection function. For instance, the material may alternatively be or include a hydrogen-rich aromatic polymer material such as, for example, polyp-xylylene) polymer (also referred to herein as parylene) or polystyrene.

[0071] Note that the low-temperature, high-pressure chemical vapor deposition process employed to deposit the neutron-responsive material within cavities **416** advantageously facilitates filling the cavities without defects and thereby, enhances the efficiency of the resultant neutron-detecting structure. Although the modified deposition conditions accomplish an efficient filling of the cavities, one skilled in the art will note that with high-aspect-ratio depositions, a tear-shaped void may be created within one or more of the cavities. In the event of such an occurrence, a small portion of the neutron-responsive material may be etched using any suitable etching processing, for example, reactive ion etching, while protecting the remaining neutron-responsive material within the cavities, for instance, using a photoresist material, and subsequently be re-deposited until the tear-shaped void is removed. Alternatively, one or more small voids within the cavities may remain in place without significantly affecting operation of the resultant neutron-detecting structure.

[0072] As depicted in FIG. 4F, the neutron-responsive material **426** may be etched back or partially removed and conductive contacts **427**, **428** may be provided on opposite sides of the structure. Note that, in one embodiment, conductive contact **427** resides over high-conducting p^+ region **408**, and conductive contact **428** resides over the opposite side, that is, over high-conducting n^- region **404** of the substrate. Note also that conductive contacts **427**, **428** may be formed of any of a variety of conductive materials, such as tungsten, titanium, copper, aluminum, molybdenum etc. Although not depicted, one skilled in the art will recognize that a silicide may be formed, for instance, by providing polysilicon over p^+ region **408** and over n^+ region **404** of the substrate, prior to the deposition of the conductive contacts. As noted above, polysilicon reacts chemically with the silicon of p^+ region **408** and the silicon of n^+ region **404** to form silicide over the p^+ region and the n^+ region. In one example, the polysilicon deposited over p^+ region **408** and n^+ region **404**, may have thickness in the range of about 30-50 nm, while conductive contacts **427**, **428** may have thickness in the range of about 50 to 100 nm. Note that, if provided, the polysilicon will also act as a buffer layer in preventing the diffusion of conductive contacts **427**, **428** into the underlying p^+ and n^+ regions, during subsequent fabrication processing.

[0073] Those skilled in the art will note from the above discussion that neutron-detector structures are provided herein with reduced leakage current. These neutron-detector structures with reduced leakage current advantageously enable large collection surfaces to be fabricated employing, for instance, a single preamplifier, by electrically connecting multiple neutron-detector structures or modules in series. Further, formation of a continuous p-n junction within the neutron-detector structure disclosed enables the three-dimensional, micro-structured, solid-state, neutron-detector to be operated at minimal or zero bias voltage, thereby providing a low-power consumption detector, and a low-noise detection capability, which significantly simplifies electronic circuit design. In one example, the thermal neutron-detection efficiency and gamma-to-neutron sensitivity were observed to be about 26±0.5% and $(1.1\pm0.1)\times10^{-5}$, respectively. Additionally, in certain embodiments, the plurality of cavities is a plurality of hexagonal-cross-sectional-shaped cavities arrayed in a honeycomb pattern, which facilitates absorbing thermal neutrons in a radial direction. The honeycomb pattern also avoids any possible streaming effects, as well as assisting in mechanical stability of neutron-detecting structure. As noted, multiple neutron-detecting structures may be electrically coupled in series to reduce the overall capacitance of the neutron-detecting sensor, and in turn, reduce noise. The detectors and fabrication methods disclosed herein facilitate neutron-detecting sensors with large detection surface areas.

[0074] The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the invention. As used herein, the singular forms “a”, “an” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms “comprise” (and any form of comprise, such as “comprises” and “comprising”), “have” (and any form of have, such as “has” and “having”), “include” (and any form of include, such as “includes” and “including”), and “contain” (and any form contain, such as “contains” and “containing”) are open-ended linking verbs. As a result, a method or device that “comprises”, “has”, “includes” or “contains” one or more steps or elements possesses those one or more steps or elements, but is not limited to possessing only those one or more steps or elements. Likewise, a step of a method or an element of a device that “comprises”, “has”, “includes” or “contains” one or more features possesses those one or more features, but is not limited to possessing only those one or more features. Furthermore, a device or structure that is configured in a certain way is configured in at least that way, but may also be configured in ways that are not listed.

[0075] The corresponding structures, materials, acts, and equivalents of all means or step plus function elements in the claims below, if any, are intended to include any structure, material, or act for performing the function in combination with other claimed elements as specifically claimed. The description of the present invention has been presented for purposes of illustration and description, but is not intended to be exhaustive or limited to the invention in the form disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art without departing from the scope and spirit of the invention. The embodiment was chosen and described in order to best explain the principles of one or more aspects of the invention and the practical application, and to enable others of ordinary skill in the art to understand one or more aspects of the invention for various embodiments with various modifications as are suited to the particular use contemplated.

What is claimed is:

1. An apparatus comprising:

a neutron-detecting structure, the neutron-detecting structure comprising:

a substrate comprising a plurality of cavities extending into the substrate from a surface thereof;

a p-n junction within the substrate and extending, at least in part, in spaced opposing relation to inner cavity walls of the substrate defining the plurality of cavities therein; and

a neutron-responsive material disposed within the plurality of cavities, the neutron-responsive material being responsive to neutrons absorbed thereby for releasing ionizing radiation reaction products, wherein the p-n junction within the substrate spaced in opposing relation to and extending, at least in part, along the inner cavity walls of the substrate reduces leakage current of the neutron-detecting structure.

2. The apparatus of claim **1**, wherein the p-n junction within the substrate is a continuous p-n junction, the continuous p-n junction being disposed, in part, parallel to the surface of the substrate from which the plurality of cavities extend into the substrate, as well as in spaced opposing relation to the inner cavity walls of the substrate.

3. The apparatus of claim **2**, wherein the continuous p-n junction is spaced from the surface of the substrate a greater distance than the continuous p-n junction is spaced in opposing relation to the inner cavity walls of the substrate.

4. The apparatus of claim **2**, wherein, in operation, the substrate comprises a depletion region, the depletion region extending within the substrate to at least a depth of the plurality of cavities within the substrate.

5. The apparatus of claim **4**, wherein the depletion region of the substrate resides, at least in part, within an n^- region of the substrate, the n^- region of the substrate being above an n^- region of the substrate.

6. The apparatus of claim **1**, wherein at least one cavity of the plurality of cavities within the substrate is, at least in part, a hexagonal-cross-sectional-shaped cavity.

7. The apparatus of claim **1**, wherein the plurality of cavities are arrayed, at least in part, in a honeycomb pattern within the substrate.

8. The apparatus of claim **1**, further comprising multiple neutron-detecting structures, the neutron-detecting structure being one neutron-detecting structure of the multiple neutron-detecting structures, and wherein the multiple neutron-detecting structures are electrically coupled in series.

9. The apparatus of claim **1**, wherein the neutron-detecting structure is designed to operate at zero bias voltage.

10. A method comprising:

fabricating a neutron-detecting structure, the fabricating comprising:

providing a substrate comprising a plurality of cavities extending into the substrate from a surface thereof;

forming a p-n junction within the substrate and extending, at least in part, in spaced opposing relation to inner cavity walls of the substrate defining the plurality of cavities therein, the p-n junction within the substrate spaced in opposing relation to and extending, at least in part, along the inner cavity walls of the substrate reducing leakage current of the neutron-detecting structure; and

providing a neutron-responsive material within the plurality of cavities, the neutron-responsive material being responsive to neutrons absorbed thereby for releasing ionization radiation reaction products.

11. The method of claim **10**, wherein forming the p-n junction comprises depositing a conformal layer of p-type dopant material at a first temperature, and subsequently annealing the conformal layer of p-type dopant material at a second temperature, the second temperature being higher than the first temperature, and the annealing facilitating forming a continuous p-n junction extending, at least in part, within the substrate in spaced opposing relation to the inner cavity walls of the substrate.

12. The method of claim **11**, wherein the second temperature is at least about 100° C. to 300° C. higher than the first temperature.

13. The method of claim **11**, wherein the conformal layer of p-type dopant material comprises a conformal layer of neutron-responsive material deposited within the plurality of cavities, the conformal layer of neutron-responsive material comprising at least one of enriched boron or a compound including enriched boron.

14. The method of claim **11**, wherein the continuous p-n junction is deposited, in part, in spaced opposing relation to the surface of the substrate, the continuous p-n junction being spaced from the surface of the substrate a greater distance than the continuous p-n junction is spaced from the inner cavity walls of the substrate.

15. The method of claim **10**, wherein at least one cavity of the plurality of cavities within the substrate is, at least in part, a hexagonal-cross-sectional-shaped cavity.

16. The method of claim **10**, wherein providing the substrate further comprises arraying, at least in part, the plurality of cavities in the substrate in a honeycomb pattern.

17. The method of claim **10**, wherein fabricating the neutron-detecting structure comprises fabricating the neutron-detecting structure to operate at zero bias voltage.

18. The method of claim **10**, wherein the neutron-responsive material within the plurality of cavities comprises a hydrogen-rich aromatic polymer material.

19. The method of claim **10**, wherein forming the p-n junction within the substrate comprises disposing a conformal layer of material over the substrate and within the plurality of cavities extending therein, and annealing the conformal layer of material to form, at least in part, the p-n junction within the substrate.

20. The method of claim **19**, further comprising removing the conformal layer of material from the plurality of cavities after the annealing and before the providing of the neutron-responsive material within the plurality of cavities.

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