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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
8 July 2010 (08.07.2010)

PCT

(10) International Publication Number
WO 2010/078221 A2

(51) International Patent Classification:
G01T 1/20 (2006.01) *G01T 1/202* (2006.01)
C09K 11/08 (2006.01) *C09K 11/77* (2006.01)

(21) International Application Number:
PCT/US2009/069533

(22) International Filing Date:
24 December 2009 (24.12.2009)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
61/141,580 30 December 2008 (30.12.2008) US

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

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (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, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

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

WO 2010/078221 A2

(54) Title: SCINTILLATION DEVICE AND METHOD OF PRODUCING A CERAMIC SCINTILLATOR BODY

(57) Abstract: A scintillation device includes a ceramic scintillator body that includes a polycrystalline ceramic scintillating material comprising gadolinium. The polycrystalline ceramic scintillating material is characterized by a pyrochlore crystallographic structure. A method of producing a ceramic scintillator body includes preparing a precursor solution including a rare earth element precursor, a hafnium precursor, and an activator (Ac) precursor. The method also includes obtaining a precipitate from the solution and calcining the precipitate to produce a polycrystalline ceramic scintillating material including the rare earth element, hafnium, and the activator, and having a pyrochlore titrating the precursor solution into the precipitant solution structure.

SCINTILLATION DEVICE AND METHOD OF PRODUCING A CERAMIC SCINTILLATOR BODY

FIELD OF THE DISCLOSURE

[0001] The present disclosure is directed to scintillation devices, particularly ruggedized scintillation devices for industrial applications, and to methods of producing ceramic scintillator bodies.

BACKGROUND

[0002] Scintillation devices are used in a variety of industrial applications. For example, scintillation devices are used for well logging in the oil and gas industry and for imaging scans in the medical field. Typically, scintillation devices include scintillator bodies, such as a scintillator crystal, produced from a material that is effective to detect gamma rays, x-rays, ultraviolet radiation or other radiation. The scintillator bodies can absorb x-rays or other radiation and emit light. The emitted light can sometimes be recorded on film. Generally, the scintillator bodies are enclosed in casings or sleeves that include a window to permit radiation-induced scintillation light to pass out of the crystal package. The light passes to a light-sensing device such as a photomultiplier tube, a photodiode, or another photosensor that converts the light emitted from the scintillator body into electrical pulses. In other applications, multiple scintillator bodies can be used in imaging arrays for medical imaging equipment.

BRIEF DESCRIPTION OF THE DRAWINGS

[0003] The present disclosure may be better understood, and its numerous features and advantages made apparent to those skilled in the art by referencing the accompanying drawings.

[0004] FIG. 1 is an illustration of a particular embodiment of a radiation detector device;

[0005] FIG. 2 is an illustration of a particular embodiment of a computed tomography (CT) device; and

[0006] FIG. 3 is a flow diagram illustrating a particular embodiment of a method of producing a ceramic scintillator body.

[0007] The use of the same reference symbols in different drawings indicates similar or identical items.

DETAILED DESCRIPTION OF THE DRAWINGS

[0008] Numerous innovative teachings of the present application will be described with particular reference to exemplary embodiments. However, it should be understood that this class of embodiments provides only a few examples of the many advantageous uses of the innovative teachings herein. In general, statements made in the specification of the present application do not necessarily limit any of the various claimed articles, systems, or methods. Moreover, some statements may apply to some inventive features but not to others.

[0009] The demands of well logging and medical imaging benefit from scintillation devices that are accurate under harsh and fast conditions. Various classes of scintillating materials can be used to produce scintillator bodies depending on intended applications. For example, single crystal oxyorthosilicates, such as lutetium yttrium oxyorthosilicate (LYSO), are often used in medical imaging applications, such as positron emission tomography (PET). These materials are typically characterized by relatively high stopping power and fast decay times. Nonetheless, LYSO is often characterized by low light output, and performance in PET scan applications can suffer from electron emission resulting from the β^- decay of lutetium.

[0010] Another class of scintillating materials includes ceramic rare earth sulfoxylates, such as gadolinium oxysulfide (GOS). Ceramic materials such as GOS can be less costly than single crystal materials, such as LYSO. However, the hexagonal structure of ceramic rare earth sulfoxylates often causes "birefringence," or light scattering at grain boundaries. As a result, such materials are less transparent and exhibit less light output or brightness than many single crystal materials. Consequently, improvements in scintillator efficiency and brightness that might be caused by the compatibility of ceramic rare earth sulfoxylates with certain activators are typically diminished by the reduced transparency that results from their hexagonal structures.

[0011] Yet another class of scintillating materials includes ceramic rare earth oxides, such as lutetium or yttrium oxides, or gadolinium lutetium oxide or gadolinium yttrium oxide. Cubic lattice structures give these materials a high degree of transparency, which increases their light output. Nonetheless, atomic distances in most ceramic rare earth oxides are shorter than ceramic rare earth sulfoxylates, for example, which causes non-radiative relaxation of some fast activators, such as cerium. Non-radiative relaxation reduces scintillator efficiency, as the activator decays without emitting visible light. Hence, the shorter atomic distances of cubic ceramic rare earth oxides tend to diminish scintillator efficiency and brightness that might result from the transparency of such materials.

[0012] FIG. 1 shows a particular embodiment of a radiation detector device 100. The radiation detector device 100 includes a photosensor 101, a light pipe 103, and a scintillation device 105. Though the photosensor 101, the light pipe 103, and the scintillation device 105 are illustrated separately from each other, it is to be understood that the photosensor 101 and the scintillation device 105 are adapted to be coupled to each other via the light pipe 103.

[0013] In one embodiment, the photosensor 101 includes a device capable of spectral detection and resolution. For example, the photosensor 101 can comprise a conventional photomultiplier tube (PMT), a hybrid photodetector, or a photodiode. The photosensor 101 is adapted to receive photons emitted by the scintillation device 105 after absorbing x-rays or other radiation, and the photosensor 101 is adapted to produce electrical pulses or imaging signals from photons that it receives.

[0014] The electronics 130 can include one or more electronic devices, such as an amplifier, a pre-amplifier, a discriminator, an analog-to-digital signal converter, a photon counter, another electronic device, or any combination thereof. The photosensor 101 can be housed within a tube or housing made of a material capable of protecting electronics associated with the photosensor 101, such as a metal, metal alloy, other material, or any combination thereof.

[0015] As illustrated, the light pipe 103 is disposed between the photosensor 101 and the scintillation device 105 and facilitates optical coupling between the photosensor 101 and the scintillation device 105. In one embodiment, the light pipe 103 can

include a quartz light pipe, plastic light pipe, or another light pipe. In another embodiment, the light pipe 103 can comprise a silicone rubber interface that optically couples an output window 119 of the scintillation device 105 with an input window of the photosensor 101. In some embodiments, multiple light pipes can be disposed between the photosensor 101 and the scintillation device 105.

[0016] The scintillation device 105 includes a scintillator body 107 housed within a casing 115. The scintillator body 107 can have various shapes, such as a rectangular shape, or a cylindrical surface including flat end faces. It will be appreciated that the surface finish of the scintillator body 107 can be sanded, polished, ground, etc., as desired.

[0017] The scintillator body 107 has a length that extends from a first end that is proximal to the photosensor 101 and a second end that is distal from the photosensor 101. The scintillation device 105 also includes a reflector 109 substantially surrounding the scintillator body 107. In addition, the scintillation device 105 can include a boot 111 that acts as a shock absorber to prevent damage to the scintillator body 107. The boot 111 can comprise a polymer, such as silicone rubber, another material, or a combination thereof. Further, the scintillation device 105 can also include a casing 113.

[0018] The scintillator body 107 is a ceramic scintillator body that includes a polycrystalline ceramic scintillating material containing a rare earth element. The polycrystalline ceramic scintillating material is characterized by a pyrochlore crystallographic structure and includes a chemical composition that can be represented by a general formula of $A_2X_2O_7$:Ac or $A_2X_2O_6O'$:Ac, where A_2 includes a rare earth element. The rare earth element can be characterized by an atomic radius greater than approximately 175 pm, such as greater than or equal to approximately 180 pm or greater than or equal to approximately 195 pm. In a particular embodiment, A_2 can include gadolinium. In other embodiments, A_2 can represent a combination of gadolinium and another rare earth element. The other rare earth element can be characterized by an atomic radius greater than approximately 175 pm, such as greater than or equal to approximately 180 pm or greater than or equal to approximately 195 pm. In addition, the scintillating material includes a quatrovalent element, represented by X, such as hafnium. For instance, the scintillator body 107

can include a rare earth hafnate (or rare earth hafnium oxide) ($A_2Hf_2O_7$), such as gadolinium hafnate $Gd_2Hf_2O_7$.

[0019] As represented in the general formula, the chemical composition of the scintillating material also includes an activator, Ac. The activator causes the scintillator body 107 to emit visible light after absorbing gamma radiation, x-rays, ultraviolet radiation, or other radiation. The activator can include a rare earth element, such as a lanthanide element. For example, the activator can include cerium, europium, praseodymium, samarium, terbium, or ytterbium. In another embodiment, the activator can include titanium. In an illustrative embodiment, the activator comprises less than or equal to approximately ten percent (10%) of the scintillating material, such as less than or equal to approximately five percent (5%) or less than or equal to approximately two percent (2%) of the scintillating material.

[0020] In an illustrative embodiment, the scintillator body 107 can be characterized by a grain size of from approximately 1 μm to approximately 100 μm. Additionally, the scintillator body 107 can also be characterized by a density of greater than 98%, such as greater than or equal to 99.9%, of theoretical density. In addition, the scintillator body 107 can be characterized by an optical transmittance of greater than fifty percent (50%) total transmission at a scintillator body thickness that stops greater than 98% of x-ray or other radiation at a wavelength of maximum emission. Moreover, the scintillator body 107 can be characterized by a decay time of less than 1 ms. The scintillator body 107 can also be characterized by a high stopping power, such as with an atomic number (eff Z) of greater than approximately 62.

[0021] FIG. 2 illustrates a particular embodiment of x-ray scanning equipment 200, such as x-ray computed tomography (CT) equipment. The x-ray scanning equipment 200 includes an array 202 of scintillator devices, or pixels, and a segmented photodetector 210. The x-ray scanning equipment 200 also includes an x-ray source 206 adapted to emit x-rays 204, e.g., in a fan-shaped or cone-shaped pattern. The x-ray source 206 and the array 202 of scintillator devices may be adapted to rotate about an object 208. For example, the x-ray source 206 and the array 202 may be adapted to rotate opposite each other substantially along a circle centered about the object 208 and at substantially equal rates.

[0022] In a particular embodiment, each pixel in the array 202 includes a scintillator body. Each scintillator body is adapted to absorb x-rays 204 emitted by the x-ray source 206 and to emit scintillation light 214 that feeds into the segmented photodetector 210. The segmented photodetector 210 is adapted to measure scintillation light 214 received from each pixel and to determine from which pixel the particular scintillation light is received. The segmented photodetector 210 is adapted to produce signals based on the amount of scintillation light emitted by each pixel in the array 202 from various angles and to send the signals to the computing device 212. The computing device 212 is adapted to construct an image of the object 208 based on the signals received from the segmented photodetector 210.

[0023] Each pixel in the array 202 includes a ceramic scintillator body that comprises a polycrystalline ceramic scintillating material containing a rare earth element. The polycrystalline ceramic scintillating material is characterized by a pyrochlore crystallographic structure and includes a chemical composition that can be represented by a general formula of $A_2X_2O_7$ or $A_2X_2O_6O'$, where A_2 includes a rare earth element. In a particular embodiment, A_2 can include gadolinium. In other embodiments, A_2 can include a combination of gadolinium and another rare earth element. In addition, the scintillating material includes a quatrovalent element, represented by X, such as hafnium. For instance, the ceramic scintillator body can include a rare earth hafnate (or rare earth hafnium oxide) ($A_2Hf_2O_7$), such as gadolinium hafnate $Gd_2Hf_2O_7$.

[0024] As represented in the general formula, the chemical composition of the scintillating material also includes an activator, Ac. The activator can include a rare earth element, such as a lanthanide element. For example, the activator can include cerium, europium, praseodymium, samarium, terbium, or ytterbium. In another embodiment, the activator can include titanium. In an illustrative embodiment, the activator comprises less than or equal to approximately ten percent (10%) of the scintillating material, such as less than or equal to approximately five percent (5%) or less than or equal to approximately two percent (2%) of the scintillating material.

[0025] In an illustrative embodiment, each scintillator body in the array 202 can be characterized by a grain size of from approximately 1 μm to approximately 100 μm. Additionally, each scintillator body can also be characterized by a density of greater

than 98%, such as greater than or equal to 99.9%, of theoretical density. In addition, each scintillator body can be characterized by an optical transmittance of greater than fifty percent (50%) total transmission at a scintillator body thickness that stops greater than 98% of x-ray or other radiation at a wavelength of maximum emission. Moreover, each scintillator body can be characterized by a decay time of less than 1 ms. Each scintillator body can also be characterized by a high stopping power, such as with an atomic number (eff Z) of greater than approximately 62.

[0026] FIG. 3 is a flow diagram illustrating a particular embodiment of a method of producing a ceramic scintillator body. At block 300, a precursor solution is prepared including a rare earth element precursor mixed with a hafnium precursor and an activator (Ac) precursor. In an illustrative embodiment, the rare earth element precursor comprises a gadolinium precursor, such as gadolinium nitrate or gadolinium chloride. In another illustrative embodiment, the rare earth element precursor can comprise a lanthanum precursor, such as lanthanum nitrate or lanthanum chloride. The hafnium precursor comprises hafnium chloride ($HfCl_4$), hafnium oxynitrate ($HfO(NO_3)_2$), anhydrous hafnium nitrate ($Hf(NO_3)_4$) or a combination thereof.

[0027] Moving to block 302, a precipitant solution is prepared. The precipitant solution can include ammonium hydroxide (NH_4OH), ammonium bicarbonate (NH_4HCO_3), or a combination thereof. In another embodiment, the precipitant solution can include oxalic acid ($H_2C_2O_4$). Proceeding to block 304, the precursor solution is titrated into the precipitant solution (or vice versa) to form a precipitate. Continuing to block 306, the precipitate is filtered and washed, and a precipitate wet cake is obtained. For example, the precipitate can be washed using deionized water until a desired conductivity value of residual ions is reached. In another example, the precipitate can also be washed with ethanol to prevent agglomeration during drying.

[0028] Advancing to block 308, the precipitate wet cake is dried to obtain a precipitate dry cake. At block 310, the precipitate dry cake is calcined to obtain a ceramic scintillating powder having a composition represented by the general formula $A_2Hf_2O_7$:Ac. For example, the composition can be represented by a general formula of $Gd_2Hf_2O_7$:Ti.

[0029] Moving to block 312, the calcined powder can be formed into ceramic scintillator bodies by first die pressing the powder into pellets and then cold isostatic pressing the pellets. Proceeding to block 314, the pressed pellets are sintered to obtain sintered samples, and each sintered sample is hot isostatic pressed. Advancing to block 316, in a particular embodiment, each sample is air annealed to improve transparency. The method terminates at 318.

EXAMPLE

[0030] In one example, a precipitant solution of ammonium hydroxide (NH_4OH) and ammonium bicarbonate (NH_4HCO_3) was prepared by adding 3M NH_4OH and 1M NH_4HCO_3 to a beaker and mixing to form a uniform complex precipitant solution, diluted to approximately 500ml. Next, a solution of precursor nitrates was prepared by mixing correct proportions of $Gd(NO_3)_3$, $HfO(NO_3)_2$, and $Ce(NO_3)_3$, diluted to 1.5L. The precursor solution was titrated into the precipitant solution to form a precipitate. The precipitate was filtered from solution and washed with deionized water and Ethanol.

[0031] The precipitate wet cake was dried in an oven at approximately 60°C, and the dried cake was calcined at 850°C for 2hrs in order to form a scintillating material having a composition of $Gd_2Hf_2O_7$:Ce.

[0032] The calcined powder was formed into ceramic scintillator bodies by first die pressing the powder into approximately 12mm diameter pellets and then cold isostatic pressing the pellets to approximately 30ksi (2.07×10^8 Pa). The pressed pellets were then sintered in air at between 1500°C and 1600°C for 3hrs. Each sintered sample was then hot isostatic pressed at between 1400°C and 1600°C for 1hr in Argon at approximately 30ksi to produce a ceramic scintillator body.

[0033] It is found that characteristics of the powder scintillating material can affect density and transparency of the resulting scintillator body. Some prior methods aim to produce powders having a uniform distribution of extremely small particles one the order of 1-5 nm in diameter, while other prior methods mix large (e.g., greater than 500 nm) and small (1-5 nm) sizes to attempt to fill any gaps between particles. However, it is found that a powder having substantially spherical particles between 10

nm and 500 nm, with a narrow particle size distribution is advantageous. For instance, a powder scintillating material having substantially spherical particles, where at least ninety percent of the particles have a size between approximately 50 nm and approximately 250 nm, such as approximately 66 nm to approximately 220 nm, can be used to produce a scintillator body having increased density and transparency. For instance, the scintillator body can be characterized by a density of greater than 98%, such as greater than or equal to 99.9%, of theoretical density. In another example, the scintillator body can be characterized by an optical transmittance of greater than fifty percent (50%) total transmission at a scintillator body thickness that stops greater than 98% of x-ray or other radiation at a wavelength of maximum emission.

[0034] In accordance with the embodiments described herein, a scintillation device is provided that comprises a ceramic scintillator body containing a polycrystalline ceramic scintillating material that includes a rare earth element and that is characterized by a pyrochlore crystallographic structure. The pyrochlore crystallographic structure can include a first sublattice comprising a plurality of rhombohedra, where each rhombohedron includes a rare earth element A coordinated by six O and two O' atoms. The pyrochlore lattice structure also includes a second sublattice comprising a plurality of distorted octahedra, where each distorted octahedron includes a cation X coordinated with six O elements and two O vacancies. The vacancies cause corner-sharing among adjacent X atoms. The coordination environment around each O element comprises a distorted tetrahedron including two A atoms and two X atoms.

[0035] The scintillator device emits visible light in proportion to the intensity of radiation absorbed by the ceramic scintillator body. The visible light can be collected by a photosensor (e.g., a photodiode, photomultiplier tube, or other photosensor) and can be converted into electrical signals for use in measurement while drilling (MWD) applications or in medical imaging applications, such as for computed tomography (CT) or positron emission tomography (PET).

[0036] In a particular embodiment, the polycrystalline ceramic scintillating material includes a rare earth hafnate, such as gadolinium hafnate, doped with an activator that includes a second rare earth element or titanium. Typically, as the atomic radius of a

rare earth element approaches that of hafnium, a rare earth hafnate will exhibit a disordered structure. As the atomic radius of the rare earth element increases, particularly above 175 pm, the rare earth hafnate structure becomes ordered but not necessarily cubic. Gadolinium hafnate exhibits a pyrochlore structure, which is more cubic than other rare earth hafnates. This more cubic structure causes gadolinium hafnate to exhibit higher degrees of transparency when used in scintillator bodies. Increased transparency allows visible light produced by the scintillator body to escape, such that it can be measured or recorded on film.

[0037] At the same time, the relatively high density of gadolinium hafnate contributes to its relatively high stopping power compared to other scintillating materials, with gadolinium hafnate exhibiting even greater stopping power than lanthanum hafnate. That is, the scintillating material is able to absorb a higher proportion of radiation, such as gamma rays or X-rays, than lower density materials. In addition, gadolinium hafnate is compatible with "fast" activators, such as cerium, neodymium, europium, terbium, titanium, and other activators, which cause fast decay of excited valence electrons that emit photons as they move from a higher energy state to a lower energy state. Fast activators are necessary in PET, CT and other applications where high numbers of individual pulses are counted despite short scan times.

[0038] Ceramic materials can be characterized by lower production costs than other scintillating materials. Nonetheless, it can be difficult to produce ceramic crystals that are sufficiently transparent to allow visible light emitted by excited valence electrons to pass from the crystal to a photosensor for measurement. This is particularly true where high-density crystals are desired. It has been found that formation of powders that contain rare earth hafnates and dopants, through co-precipitation, enables production of ceramic scintillating crystals using ceramic processes, such as sintering, hot forging, hot pressing, or other ceramic firing processes. Such ceramics exhibit good stopping power and light output.

[0039] Starting powder quality has a significant impact on final performance of polycrystalline ceramic scintillator bodies, particularly with respect to properties such as optical transmittance, afterglow, and light output. Solid state reaction and combustion methods can be used to produce scintillator bodies formed from

lanthanum hafnate, for example, but both methods have drawbacks, such as control over grain size and safety issues.

[0040] It is found that a co-precipitation process provides desired chemical homogeneity of a ceramic scintillating powder material. Co-precipitation has been used with respect to Y_2O_3 stabilized ZrO_2. However, co-precipitation with respect to lanthanum hafnate, for instance, requires a strict chemical stoichiometric ratio of lanthanum oxide to hafnium oxide, and solubility product constants of precursors, such as $La(OH)_3$ and $Hf(OH)_4$ differ significantly. Hence, it is typically difficult to precipitate lanthanum and hafnium simultaneously.

[0041] It is found that titrating a precursor solution that includes, for example, lanthanum nitrate, hafnium oxynitrate and an activator precursor into a precipitant solution of ammonium hydroxide, ammonium bicarbonate, oxalic acid, oxalates, urea, or any combination thereof, yields co-precipitated lanthanum, hafnium and activator.

[0042] The illustrations of the embodiments described herein are intended to provide a general understanding of the structure of the various embodiments. The illustrations are not intended to serve as a complete description of all of the elements and features of the structures or methods described herein. Many other embodiments may be apparent to those of skill in the art upon reviewing the disclosure. Other embodiments may be utilized and derived from the disclosure, such that structural and logical substitutions and changes may be made without departing from the scope of the disclosure. Additionally, the illustrations are merely representational and may not be drawn to scale. Certain proportions within the illustrations may be exaggerated, while other proportions may be minimized. Accordingly, the disclosure and the Figures are to be regarded as illustrative rather than restrictive.

[0043] According to a first aspect, a scintillation device comprises a ceramic scintillator body that includes a polycrystalline ceramic scintillating material comprising gadolinium. The polycrystalline ceramic scintillating material is characterized by a pyrochlore lattice structure. In one embodiment of the first aspect, a chemical composition of the polycrystalline ceramic scintillating material is represented by a formula of $A_2X_2O_7$:Ac, where Ac is an activator and A_2 includes gadolinium.

[0044] In an embodiment of the first aspect, A_2 includes gadolinium and another rare earth element. The other rare earth element can be characterized by an atomic radius greater than or equal to 180 pm, such as greater than or equal to 195 pm.

[0045] In another embodiment of the first aspect, X represents a quatrovalent element, such as hafnium. In this embodiment, the chemical composition can be represented by a general formula of $Gd_2Hf_2O_7$:Ac, where Ac is an activator. In one example, the activator comprises less than ten percent (10%) of the polycrystalline ceramic scintillating material based on molar percentage. The activator can include a rare earth element, such as a lanthanide element. For instance, the activator can include cerium, praseodymium, neodymium, europium, terbium, holmium, ytterbium, or any combination thereof. In another embodiment, the activator can include titanium.

[0046] According to a second aspect, a ceramic scintillator body includes a polycrystalline ceramic scintillating material that includes gadolinium. The polycrystalline ceramic scintillating material is characterized by a pyrochlore crystallographic structure. In one embodiment, the ceramic scintillator body is characterized by a density of at least 99.9% of theoretical density. Further, the ceramic scintillator body can be characterized by a grain size of from approximately 1 μm to approximately 100 μm. In one example, the polycrystalline ceramic scintillating material comprises gadolinium hafnate ($Gd_2Hf_2O_7$).

[0047] According to a third aspect, a method of producing a ceramic scintillator body includes preparing a precursor solution including a rare earth element precursor, a hafnium precursor, and an activator (Ac) precursor. The method also includes obtaining a precipitate from the solution and calcining the precipitate to produce a polycrystalline ceramic scintillating material including the rare earth element, hafnium, and the activator, and having a pyrochlore crystallographic structure. In one embodiment, the polycrystalline ceramic scintillating material is a powder.

[0048] Further, the method can include preparing a precipitant solution and titrating the precursor solution into the precipitant solution, or titrating the precipitant solution into the precursor solution, to obtain the precipitate. The precipitant solution can include, for example, ammonium hydroxide, ammonium bicarbonate, oxalic acid, or

any combination thereof. Further, the hafnium precursor can include hafnium chloride ($HfCl_4$), hafnium nitrate ($Hf(NO_3)_4$), or a combination thereof.

[0049] According to a fourth aspect, a ceramic scintillating powder comprises a polycrystalline ceramic scintillating material including gadolinium, where the polycrystalline ceramic scintillating material is characterized by a pyrochlore crystallographic structure. In one embodiment of the fourth aspect, the polycrystalline ceramic scintillating material comprises a plurality of substantially spherical particles and wherein at least ninety percent of the particles are characterized by a particle size of from approximately 50 nm to approximately 250 nm. For example, at least ninety percent of the particles can be characterized by a particle size of from approximately 66 nm to approximately 220 nm.

[0050] In the foregoing Detailed Description of the Drawings, various features may be grouped together or described in a single embodiment for the purpose of streamlining the disclosure. This disclosure is not to be interpreted as reflecting an intention that the claimed embodiments require more features than are expressly recited in each claim. Rather, as the following claims reflect, inventive subject matter may be directed to less than all features of any of the disclosed embodiments. Thus, the following claims are incorporated into the Detailed Description of the Drawings, with each claim standing on its own as defining separately claimed subject matter.

[0051] The above disclosed subject matter is to be considered illustrative, and not restrictive, and the appended claims are intended to cover all such modifications, enhancements, and other embodiments which fall within the true spirit and scope of the present disclosed subject matter. Thus, to the maximum extent allowed by law, the scope of the present disclosed subject matter is to be determined by the broadest permissible interpretation of the following claims and their equivalents, and shall not be restricted or limited by the foregoing detailed description.

WHAT IS CLAIMED IS:

1. A ceramic scintillator body comprising a polycrystalline ceramic scintillating material that includes gadolinium, wherein the polycrystalline ceramic scintillating material is characterized by a pyrochlore crystallographic structure.

2. A scintillation device comprising a ceramic scintillator body that includes a polycrystalline ceramic scintillating material comprising gadolinium, wherein the polycrystalline ceramic scintillating material is characterized by a pyrochlore crystallographic structure.

3. A ceramic scintillating powder comprising a polycrystalline ceramic scintillating material comprising including gadolinium, wherein the polycrystalline ceramic scintillating material is characterized by a pyrochlore crystallographic structure.

4. The ceramic scintillating powder of claim 3, wherein the polycrystalline ceramic scintillating material comprises a plurality of substantially spherical particles and wherein at least ninety percent of the particles are characterized by a particle size of from approximately 50 nm to approximately 250 nm.

5. The ceramic scintillating powder of claim 3, wherein at least ninety percent of the particles are characterized by a particle size of from approximately 66 nm to approximately 220 nm.

6. The ceramic scintillator body of claim 1, scintillation device of claim 2, or the ceramic scintillating powder of claim 3, 4, or 5, wherein a chemical composition of the polycrystalline ceramic scintillating material is represented by a general formula of $A_2X_2O_7$:Ac, where Ac is an activator and A_2 includes gadolinium.

7. The ceramic scintillator body, scintillation device, or the ceramic scintillating powder of claim 6, wherein A_2 includes gadolinium and another rare earth element.

8. The ceramic scintillator body, scintillation device, or the ceramic scintillating powder of claim 7, wherein the other rare earth element is characterized by an atomic radius greater than or equal to 180 pm.

9. The ceramic scintillator body, scintillation device, or the ceramic scintillating powder of claim 8, wherein the other rare earth element is characterized by an atomic radius greater than or equal to 195 pm.

10. The ceramic scintillator body, scintillation device, or the ceramic scintillating powder of claim 6, wherein X represents a quatrovalent element.

11. The ceramic scintillator body, scintillation device, or the ceramic scintillating powder of claim 10, wherein X represents hafnium.

12. The ceramic scintillator body, scintillation device, or the ceramic scintillating powder of claim 11, wherein the chemical composition is represented by a formula of $Gd_2Hf_2O_7$:Ac, where Ac is an activator.

13. The ceramic scintillator body, scintillation device, or the ceramic scintillating powder of claim 6, wherein the activator comprises less than ten percent (10%) of the polycrystalline ceramic scintillating material based on molar percentage.

14. The ceramic scintillator body, scintillation device, or the ceramic scintillating powder of claim 6, wherein the activator comprises a rare earth element.

15. The ceramic scintillator body, scintillation device, or the ceramic scintillating powder of claim 14, wherein the activator comprises cerium, praseodymium, neodymium, europium, terbium, holmium, or ytterbium, or any combination thereof.

16. The ceramic scintillator body, scintillation device, or the ceramic scintillating powder of claim 6, wherein the activator includes titanium.

17. The ceramic scintillator body of claim 1 or the scintillation device of claim 2, wherein the ceramic scintillator body is characterized by a density of at least 99.9% of theoretical density.

18. The ceramic scintillator body of claim 1 or the scintillation device of claim 2, wherein the ceramic scintillator body is characterized by a grain size of from approximately 1 μm to approximately 100 μm.

19. The ceramic scintillator body of claim 1, scintillation device of claim 2, or the ceramic scintillating powder of claim 3, 4, or 5, wherein the polycrystalline ceramic scintillating material comprises gadolinium hafnate ($Gd_2Hf_2O_7$).

20. A method of producing a ceramic scintillator body, the method comprising:
preparing a precursor solution including a rare earth element precursor, a hafnium precursor, and an activator (Ac) precursor;
obtaining a precipitate from the solution; and
calcining the precipitate to produce a polycrystalline ceramic scintillating material including the rare earth element, hafnium, and the activator, and having a pyrochlore crystallographic structure.

21. The method of claim 20, wherein the polycrystalline ceramic scintillating material is a powder.

22. The method of claim 20, further comprising:
preparing a precipitant solution; and
titrating the precursor solution into the precipitant solution, or titrating the precipitant solution into the precursor solution, to obtain the precipitate.

23. The method of claim 22, wherein the precipitant solution includes ammonium hydroxide, ammonium bicarbonate, oxalic acid, or any combination thereof.

24. The method of claim 20, wherein the hafnium precursor comprises at hafnium chloride ($HfCl_4$), hafnium nitrate ($Hf(NO_3)_4$), or a combination thereof.

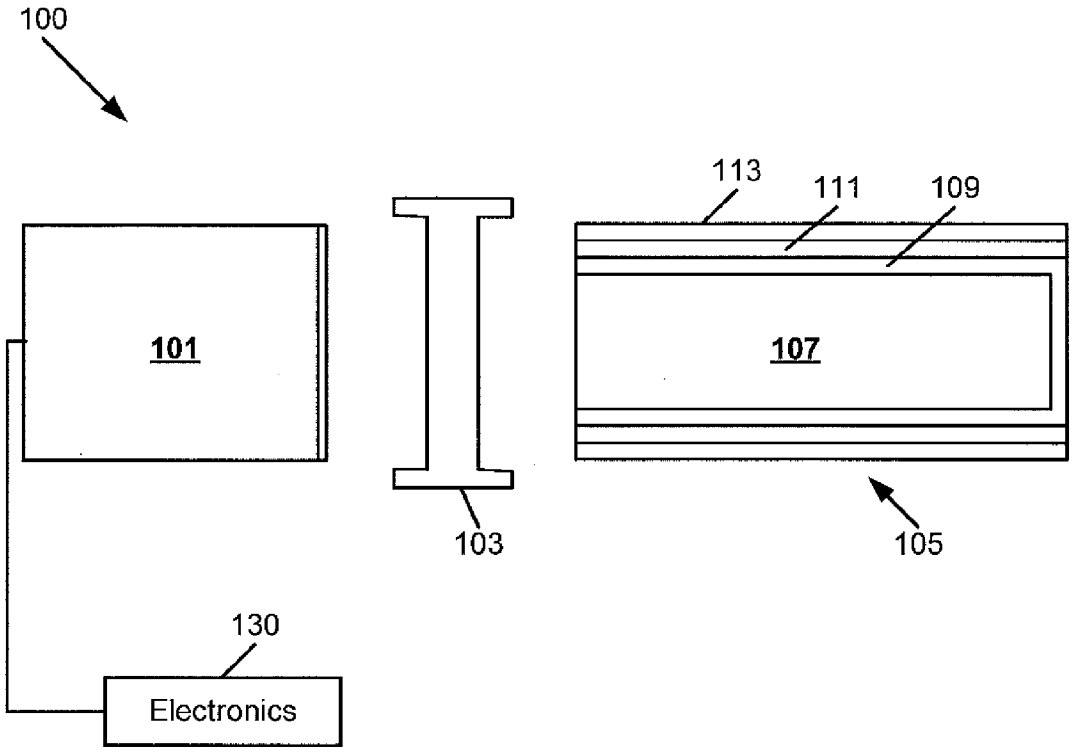

FIG. 1

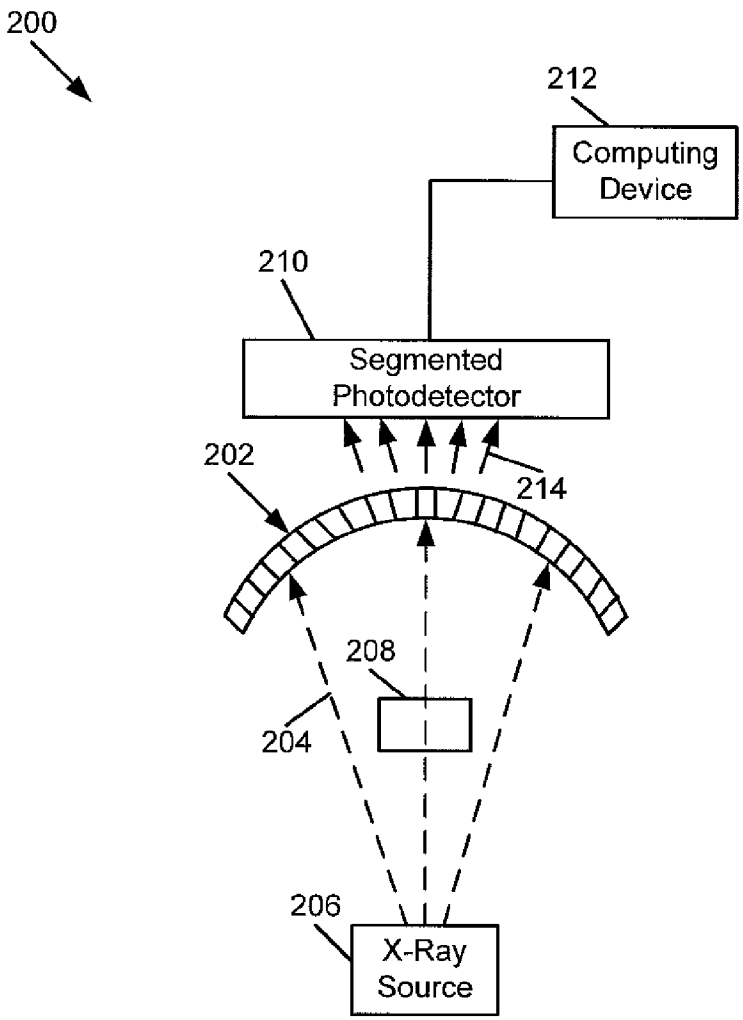
200
212
Computing Device
210
Segmented Photodetector
202
214
208
204
206
X-Ray Source

FIG. 2

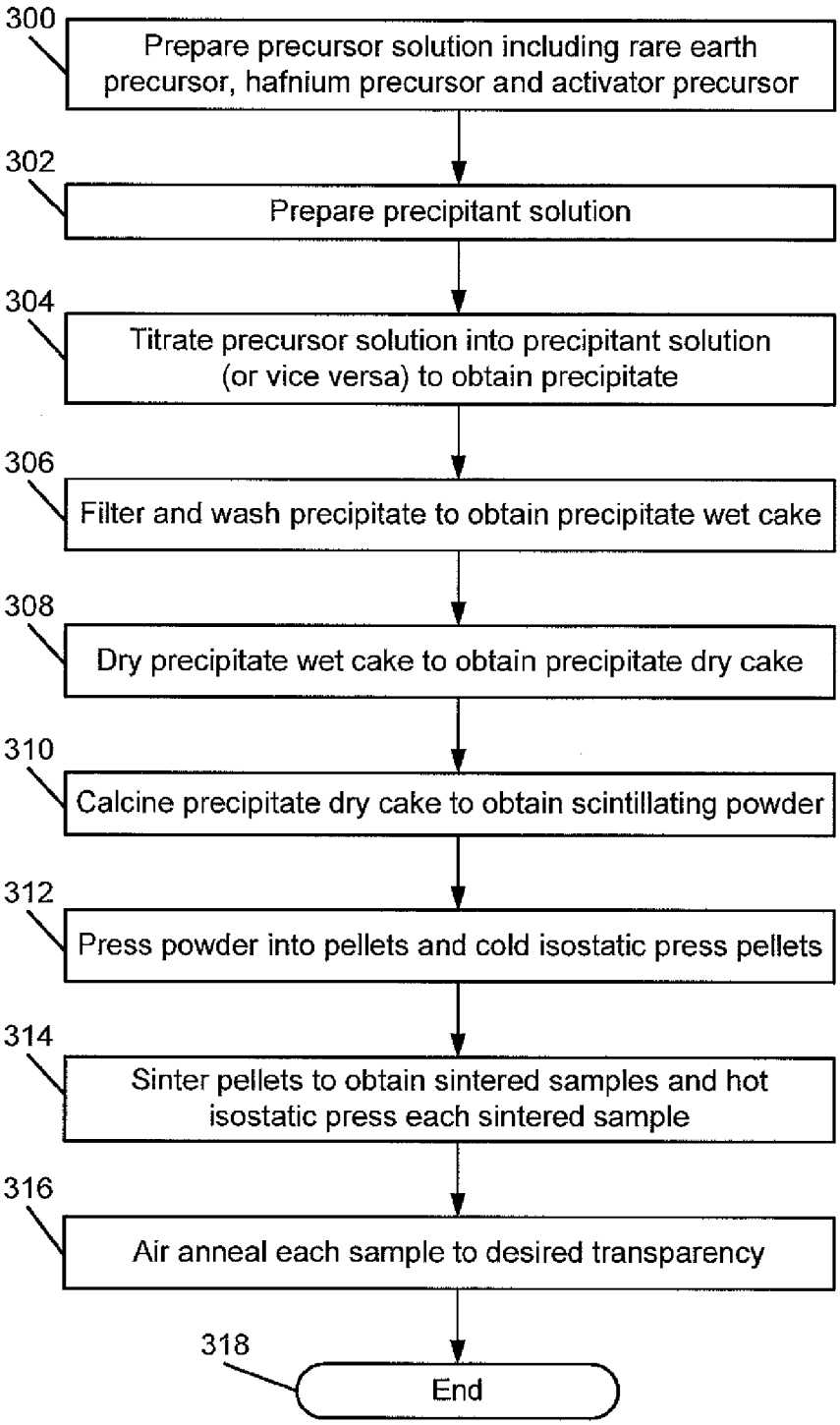
300
Prepare precursor solution including rare earth precursor, hafnium precursor and activator precursor
302
Prepare precipitant solution
304
Titrate precursor solution into precipitant solution (or vice versa) to obtain precipitate
306
Filter and wash precipitate to obtain precipitate wet cake
308
Dry precipitate wet cake to obtain precipitate dry cake
310
Calcine precipitate dry cake to obtain scintillating powder
312
Press powder into pellets and cold isostatic press pellets
314
Sinter pellets to obtain sintered samples and hot isostatic press each sintered sample
316
Air anneal each sample to desired transparency
318
End

FIG. 3