



(51) International Patent Classification:

G01T 1/02 (2006.01) *G01T 1/178* (2006.01)
G01T 1/24 (2006.01)

(21) International Application Number:

PCT/US2016/052647

(22) International Filing Date:

20 September 2016 (20.09.2016)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

62/221,546 21 September 2015 (21.09.2015) US

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(81) Designated States (*unless otherwise indicated, for every
kind of national protection available*): AE, AG, AL, AM,

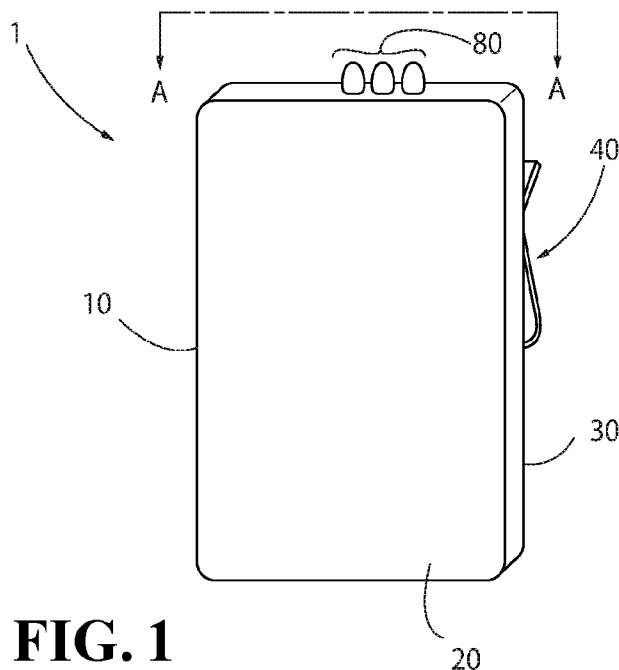
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TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM,
ZW.

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

Published:

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

(54) Title: POWER-OPTIMIZING IONIZING RADIATION DOSIMETER

**FIG. 1**

(57) Abstract: Described is a dosimeter for measuring one or more doses of radiation. The dosimeter includes a detector, a power source, and a controller. The detector can be a pixelated circuit with readout electronics. The controller is in communication with the readout electronics and is adapted to dynamically adjust a readout mode of the detector based on information received from the detector. Also described is a method of measuring one or more doses of radiation using this dosimeter. The method includes receiving, at the detector, one or more ionizing radiation photons, transmitting information about the one or more ionizing radiation photons to the controller, and dynamically adjusting, by the controller, a readout mode of the detector based on the information received about the one or more ionizing radiation photons.

POWER-OPTIMIZING IONIZING RADIATION DOSIMETER

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to United States Provisional Patent Application No. 62/221,546, filed September 21, 2015. This application also relates to United States Provisional Patent Application No. 62/191,721, filed July 13, 2015. The entire contents of each of which are expressly incorporated by reference herein.

BACKGROUND OF THE DISCLOSURE

Field of the Disclosure

[0002] This invention relates to dosimeters for measuring exposure to radiation. More particularly, this invention relates to dosimeters including power-optimizing features.

Description of Related Art

[0003] National laws and regulations generally require that workers who may be exposed to ionizing radiation be monitored for radiation exposure, and that their exposures be kept “as low as reasonably achievable.” This is known as the ALARA principle. To achieve this, passive radiation badges are commonly used, such as those described in United States Patent No. 3,655,975 to Evans, which is incorporated herein by reference. The accumulated radiation dose measured by the passive badge can be read out periodically, usually monthly. This monitoring is useful, but gives the worker no real time feedback which could be much more useful in reducing his or her radiation dose. If the worker is subject to a dose that is higher than desired, the RSO (Radiation Safety Officer) and the worker need to figure out, sooner rather than later, why the higher dose was received so as to prevent a recurrence. This is difficult and time consuming, especially given the delay between the dose incurring event and the readout of the passive badge and the return of the information. One of the attributes that is important for these “dose of record” dosimeters is that their response be proportional to that of the human body to ionizing radiation over the whole range of radiation types and energies.

[0004] Real time personal or individual alarming dosimeters are available, an example of which is a dosimeter using an integrated circuit (IC) imager. However, while available, these real time dosimeters are generally expensive. In addition, they are not usually certified to provide “dose of record” information, so they are an additional expense above the cost of a certified “dose of record” dosimeter. Thus, these real time personal dosimeters are used

sparingly, even though the real time feedback they can provide has been demonstrated to reduce worker dose.

SUMMARY

[0005] In accordance with some aspects, described is a dosimeter for measuring one or more doses of radiation that includes a detector, a power source, and a controller. The detector is a pixelated circuit with readout electronics and the controller is in communication with the readout electronics and adapted to dynamically adjust a readout mode of the detector based on information received from the detector.

[0006] In accordance with other aspects, described is a method of measuring one or more doses of radiation using a dosimeter, wherein the dosimeter includes a detector having a pixelated circuit with readout electronics, a power source, and a controller. The method includes receiving, at the detector, one or more ionizing radiation photons, transmitting information about the one or more ionizing radiation photons to the controller, and dynamically adjusting, by the controller, a readout mode of the detector based on the information received about the one or more ionizing radiation photons.

[0007] Various aspects of the present disclosure may be further characterized by one or more of the following clauses:

[0008] Clause 1. A dosimeter for measuring one or more doses of radiation, comprising: a detector, wherein the detector comprises a pixelated circuit comprising readout electronics; a power source; and a controller in communication with the readout electronics and adapted to dynamically adjust a readout mode of the detector based on information received from the detector.

[0009] Clause 2. The dosimeter of clause 1, wherein the pixelated circuit is a light imaging circuit.

[0010] Clause 3. The dosimeter of clause 1, wherein the pixelated circuit is a CCD, CMOS, or DRAM circuit comprising a plurality of pixels.

[0011] Clause 4. The dosimeter of clause 1, wherein the controller is adapted to dynamically adjust the readout mode of the detector based on one or more measurements related to dark current.

[0012] Clause 5. The dosimeter of clause 1, wherein the controller is adapted to dynamically adjust the readout mode of the detector to reduce total power usage.

[0013] Clause 6. The dosimeter of clause 1, wherein the controller is adapted to dynamically adjust the readout mode of the detector or an operating mode of the controller based on a rate at which ionizing radiation events are detected by the detector.

[0014] Clause 7. The dosimeter of clause 1, wherein the controller is adapted to dynamically adjust the readout mode of the detector based on a fault in one or more pixels, rows, columns, or segments of the detector.

[0015] Clause 8. The dosimeter of clause 1, wherein the controller is adapted to dynamically adjust the readout mode of the detector based on a temperature associated with the detector.

[0016] Clause 9. The dosimeter of clause 1, further comprising at least one filter positioned over the detector.

[0017] Clause 10. The dosimeter of clause 9, wherein a first filter is positioned over a front face of the detector and a second filter is positioned over a rear face of the detector, wherein the rear face is opposite the front face.

[0018] Clause 11. The dosimeter of clause 10, wherein the first filter and the second filter are comprised of the same filter material.

[0019] Clause 12. The dosimeter of clause 9, wherein the at least one filter is arranged so that each segment of the detector has the same effective filtering.

[0020] Clause 13. A method of measuring one or more doses of radiation using a dosimeter, wherein the dosimeter comprises a detector comprising a pixelated circuit with readout electronics, a power source, and a controller, comprising: receiving, at the detector, one or more ionizing radiation photons; transmitting information about the one or more ionizing radiation photons to the controller; and dynamically adjusting, by the controller, a readout mode of the detector based on the information received about the one or more ionizing radiation photons.

[0021] Clause 14. The method of clause 13, further comprising receiving, at the controller, one or more measurements related to dark current.

[0022] Clause 15. The method of clause 14, wherein the controller dynamically adjusts the readout mode of the detector based on the one or more measurements related to dark current.

[0023] Clause 16. The method of clause 15, wherein the controller decreases the readout rate of the detector based on the one or more measurements related to dark current.

[0024] Clause 17. The method of clause 15, wherein the controller increases the readout rate of the detector based on the one or more measurements related to dark current.

[0025] Clause 18. The method of clause 13, wherein the controller dynamically adjusts the readout mode of the detector based on a rate at which the ionizing radiation events are detected by the detector.

[0026] Clause 19. The method of clause 18, wherein the controller increases the readout rate of the detector, decreases the readout area of the detector, or both increases the readout rate and decreases the readout area of the detector if the rate at which the ionizing radiation events are detected by the detector is above a threshold level.

[0027] Clause 20. The method of clause 13, further comprising measuring a temperature associated with the detector and dynamically adjusting, by the controller, the readout mode of the detector based on the temperature associated with the detector.

[0028] Clause 21. The method of clause 13, further comprising initiating an alarm if a rate at which the ionizing radiation events are received by the detector exceeds a threshold level.

[0029] Clause 22. The method of clause 13, further comprising initiating an alarm if a total radiation dose received by the detector over a period of time exceeds a threshold level.

[0030] These and other features and characteristics of the dosimeter, as well as the methods of operation and functions of the related elements of structures and the combination of parts and economies of manufacture, will become more apparent upon consideration of the following description and the appended claims with reference to the accompanying drawings, all of which form a part of this specification, wherein like reference numerals designate corresponding parts in the various figures.

BRIEF DESCRIPTION OF THE FIGURES

[0031] The Figures associated with the present disclosure describe specific embodiments and should not be considered limiting to the overall disclosure as set forth in the claims.

[0032] **FIG. 1** illustrates a perspective view of one embodiment of a dosimeter according to the present disclosure.

[0033] **FIG. 2** illustrates a cross-sectional view of the dosimeter of **FIG. 1** taken along line A-A.

[0034] **FIG. 3** illustrates a perspective view of another embodiment of a dosimeter according to the present disclosure.

[0035] **FIG. 4** illustrates a plan view of one embodiment of a pixelated circuit for use as a detector in a dosimeter according to the present disclosure.

[0036] **FIG. 5A** illustrates a plan view of one embodiment of a detector and filter arrangement according to the present disclosure.

[0037] **FIG. 5B** illustrates a side view of the detector and filter arrangement of **FIG. 5A**.

[0038] **FIGS. 5C** and **5D** illustrate plan views of alternative embodiments of a detector and filter arrangement according to the present disclosure.

[0039] **FIGS. 6A** and **6B** are graphs illustrating the operation of a detector according to embodiments of the present disclosure.

[0040] **FIG. 7** illustrates a process diagram of one embodiment of a radiation management system according to the present disclosure.

DETAILED DESCRIPTION

[0041] The illustrations generally show preferred and non-limiting aspects of the present disclosure. While the descriptions present various aspects of the devices, systems, and/or methods described herein, it should not be interpreted in any way as limiting the disclosure. Furthermore, modifications, concepts, and applications of the disclosure's aspects are to be interpreted by those skilled in the art as being encompassed by, but not limited to, the illustrations and descriptions provided herein.

[0042] The following description is provided to enable those skilled in the art to make and use the described aspects contemplated for carrying out the disclosure. Various modifications, equivalents, variations, and alternatives, however, will remain readily apparent to those skilled in the art. Any and all such modifications, variations, equivalents, and alternatives are intended to fall within the spirit and scope of the present disclosure.

[0043] Further, for purposes of the description hereinafter, the terms “end”, “upper”, “lower”, “right”, “left”, “top”, “bottom”, and derivatives thereof shall relate to the disclosure as it is oriented in the figures. However, it is to be understood that the disclosure may assume various alternative variations and step sequences, except where expressly specified to the contrary. It is also to be understood that the specific devices and processes illustrated in the attached drawings, and described in the specification, are simply exemplary aspects of the disclosure. Hence, specific dimensions and other physical characteristics related to the aspects disclosed herein are not to be considered as limiting. For the purpose of facilitating understanding of the disclosure, the accompanying drawings and description illustrate preferred aspects thereof, from which the disclosure, various aspects of its structures, construction and method of operation, and many advantages may be understood and appreciated.

[0044] Various embodiments of this disclosure relate generally to an integrated circuit dosimeter including a detector for detecting ionizing radiation that is incident on the detector.

The terms ionizing radiation and ionizing radiation photons are used interchangeably herein. These terms may refer to, but are not limited to, photons with enough energy to ionize or create a free charge in the detector, X-rays, gamma rays, beta rays, delta rays, alpha particles, neutrons, cosmic rays, and other high energy particles, for example from an accelerator. As will be apparent from this disclosure, embodiments of the dosimeter described herein can provide real time alarming capability at a small price premium over existing passive dosimetry technology and can also provide a legal dose of record. The dosimeters described herein can be sized so as to be worn or carried by a user.

[0045] **FIGS. 1-2** show one embodiment of a dosimeter **1** according to this disclosure. Dosimeter **1** can include a housing **10** formed from a front portion **20** and a rear portion **30** wherein the front portion **20** and rear portion **30** engage with one another through a snap fit or other mechanism. Alternatively, housing **10** can be formed as a single integral piece. Within housing is an internal cavity **60**. Rear portion **30** can include a fastener **40**, such as a spring clip, strap, adhesive, VELCRO®, or other suitable structure that can be used to attach dosimeter **1** to a user's body or clothing, such as around the user's arm or to the user's pocket, shirt, or hat. **FIG. 3** shows another embodiment of dosimeter **1** in which the housing **10** is very slim, having a thickness of approximately 0.5 to 2 cm. The dosimeter of **FIG. 3** is suitable for carrying in a user's pocket, handbag, or wallet and may not include a fastener **40**, but otherwise includes similar components as the dosimeter of **FIGS. 1-2**. Housing **10** can be formed from a durable plastic material, such as polycarbonate, polyethylene, styrene, polyoxymethylene, or other suitable material or combinations thereof. Suitable metals or ceramics may be used as well.

[0046] Within internal cavity **60**, dosimeter **1** can include a detector **100** for detecting the presence of ionizing radiation photons, a controller **200** in communication with detector **100** for controlling operation of detector **100**, processing information received from detector **100**, and quantifying radiation events (i.e., the receipt of one or more ionizing radiation photons) based on such information, and a power source **300**, such as a battery, for powering dosimeter **1**. Detector **100** can have a generally flat shape with a front face **150**, and a rear face (not shown) opposite the front face **150**.

[0047] In some non-limiting embodiments, detector **100** is an integrated circuit composed of silicon with the silicon itself acting to detect the occurrence of ionizing radiation, for example gamma ray photons, or secondary rays from such radiation, either alone or in combination with other compounds. Other semiconductor compounds that may be used include germanium, cadmium zinc telluride, gallium arsenide, SiC and diamond. In other

non-limiting embodiments, the detector **100** can include a scintillator that gives off light when a photon is absorbed, or a large area photo diode which can be used to count photon pulses, particularly when the photon pulses are greater than the dark current, which is further described below.

[0048] In certain non-limiting embodiments, detector **100** can include a pixelated circuit, such as an analog or digital light imaging integrated circuit capable of detecting the presence of ionizing radiation photons. For example, the detector can be composed of an analog light imaging circuit such as a charge-coupled device (CCD) or complementary metal-oxide-semiconductor (CMOS) circuit. CCD and CMOS are well known in the art. The detector can also be a dynamic random-access memory (DRAM) with a fixed or varying reference. DRAM circuits are also well known in the art and generally operate by storing a bit of data as charge in each capacitor within the circuit. Other types of pixelated circuits may also be used, as would be understood by one of skill in the art after reading this disclosure.

[0049] With reference to **FIG. 4**, normal light imaging circuits, for example CCD or CMOS, are formed as an M by N array (M rows by N columns) of pixels **400** with associated readout electronics **500** on an integrated circuit chip or additional chips. Each pixel **400** is a two-dimensional picture element that represents one element of an area array of a display or image sensor. These conventional light imaging circuits commonly operate at normal video rates of 30 or 60 frames per second, with progressive or interlaced readout. One row is read out at a time, and when one row is completed, the next is read. A frame is generally considered to be the set of rows that are read before restarting with the initial row of the next frame. In progressive readout, every row is read in order to construct the full frame and then the readout of the next frame begins at the initial row again. During interlaced readout, every other row is read during the first frame readout, and then the alternative rows are read during the second frame readout. When a frame is read, the next frame is started. For purposes of this disclosure, the manner in which the pixels and/or rows are read, such as to constitute a frame, is referred to as the readout mode.

[0050] In light imaging circuits, such as those discussed above, a visible light photon creates one or a few electrons by being absorbed in the voxel associated with the pixel. As mentioned, a pixel refers to a picture element. In the case of a detector, a pixel can be considered to represent a detecting element. In the case of a DRAM, a pixel can also be considered to represent one memory cell. A voxel refers to a three-dimensional volume element, for example an X-ray or light absorbing material. The number of charges accumulated in a pixel represents the integral of the number of photons absorbed by that pixel

between readouts. For visible light, generally a single charge is created by a single photon, although some photons may be absorbed without a charge being created. In addition, charges may leak away. For a given constant light flux, because there are commonly many photons per pixel per frame, the integral of the charge is proportional to the area of the pixel. Ionizing radiation photons have significantly higher energy per photon than visible light, so more charges are created per photon, sometimes thousands or tens of thousands of charges per photon. The normally encountered flux rate of ionizing photons is usually at a much lower rate than for light photons, so there is commonly only one ionizing photon for a number of pixels. Thus, the signal from an ionizing photon flux is not proportional to pixel area at normally encountered flux rates, unless blooming occurs.

[0051] A significant source of noise or interference with ionizing radiation detectors is leakage current. The leakage current is dependent on the temperature of the detector and typically doubles every 5-10°C. The amount of leakage charge collected in a pixel is generally related to the area or volume of the voxel, depending upon the specific mechanisms creating the leakage currents that are significant, as is understood by those skilled in the art. For example, it is related to the band gap or ionization threshold of the materials involved, surface states, traps, dopants, impurities and other factors. One type of leakage current is dark current, which represents the leakage current that exists in a pixel when no light is incident on the pixel. Because of the high light photon flux rates, rapid readout rate, and small pixel size, leakage current is generally not a problem in normal light photon imaging situations. It can be a limitation when imaging at very low light levels, for example at night or in astronomy. However, in ionizing photon detectors of the type discussed in this disclosure, all, or virtually all, of the leakage current can be considered or treated as dark current, and, for purposes of this disclosure, the terms dark current and leakage current are considered equivalent.

[0052] According to embodiments of this disclosure, detector **100** includes one or more pixelated circuits in which the readout mode can be dynamically adjusted. For example, these adjustments can be implemented to significantly reduce power consumption while retaining the ability to rapidly sense and respond to changes in radiation exposure or flux to alert the user in a timely fashion. Techniques to adjust the readout mode can be in the form of programming instructions stored in a computer-readable medium located on or in communication with controller **200**. Controller **200** can execute these instructions to initiate or implement one or more changes in the readout mode dynamically during operation of detector **100**, such as upon recognition of one or more triggering events, as described below.

As will be appreciated, adjustments to the readout mode to, for example, reduce the power consumption of detector **100** and/or controller **200** provides significant benefits. For example, if dosimeter **1** can operate on reduced power, it requires less power to operate, and a lower capacity power source **300** can be used to power dosimeter **1**. Power source **300**, particularly when it is a battery, is a significant contributor to both the cost of dosimeter **1** and the physical size and weight of dosimeter **1**. Thus, permitting use of a lower capacity power source **300** lowers both the cost and the physical size of dosimeter **1**. In addition, if dosimeter **1** can operate on reduced power consumption, it can operate for a longer period without charging or replacing power source **300**.

[0053] One example of an adjustment that can be made to the readout mode involves reducing the frame readout rate in order to reduce power consumption. This can be accomplished by configuring readout electronics **500** to commence some pause between frame readouts, rather than automatically proceeding from frame to frame. The pause period can be for a preset period of time, at the end of which frame readout will commence. Alternatively, frame readout can pause indefinitely and commence only upon a further signal from controller **200** to commence frame readout. Controller **200** may initiate a pause period when, for example, controller **200** recognizes a low, or very low, dose rate is being received by detector **100**. In the situation where the dose rate is very low, there is less risk that an ionizing event will be missed during the pause period. Pausing the readout is one embodiment of an extended readout mode.

[0054] However, because a pause period between frame readouts adds the potential that an ionizing event could be missed if the event occurs during the pause period, the frame readout rate could instead be adjusted to proceed continually but at a slower rate. For instance, if detector **100** normally operates by reading 30 frames per second, controller **200** could adjust the frame readout to only ten frames per second, one frame per second, or even one frame per minute. The exact specifics of the frame readout rate can depend upon many properties of detector **100** as mentioned herein and as would be recognized by those skilled in the art upon reading this disclosure. These properties could be considered in programming controller **200** to control the readout rate of detector **100**. Slowing the readout rate is another embodiment of an extended readout mode.

[0055] Various factors can be used by controller **200** to dynamically adjust the readout mode by either implementing a pause period or adjusting the frame readout rate. For instance, controller **200** can continually or periodically assess the average dark current of each frame and adjust the frame rate so that the dark current per frame is some fraction, for

example between 5 and 25%, such as 10%, of the expected radiation photon absorption charge that would occur in a pixel during an ionizing event. In other words, the dark current accumulation rate can be monitored and the frame rate can be adjusted so that the dark current accumulation in the pixels does not exceed a threshold value, where the threshold value can be set between 5 and 25% of the expected radiation photon absorption charge that would be observed for an ionizing event. A pause between frame acquisitions can be increased and/or the frame rate decreased, and thus additional power saved, if the dark current is below the threshold. The pause between frame readouts can be decreased and/or the frame rate increased, at the cost of higher power consumption, if the dark current creeps above the threshold. In either case, the dark current can be monitored and assessed by controller **200** based on data received from detector **100** concerning dark current and the period between frame readouts and/or the frame readout rate can be adjusted in real time based on the assessment of dark current. There is preferably a minimum frame rate, which can be user settable or can be fixed by the manufacturer. This minimum frame readout rate may depend upon the warning latency which is acceptable in the case of a suddenly increased radiation exposure rate.

[0056] Because dark current is a function of temperature, the readout mode could also be adjusted depending on a temperature associated with detector **100**. As the temperature increases, the dark current also increases. Accordingly, if the temperature of detector **100** is higher than a baseline value, the readout mode can be adjusted to increase the frame readout rate from the rate associated with the baseline temperature. Similarly, if the temperature is below the baseline value, the frame readout rate can be decreased. The temperature of detector **100** can be measured by a thermometer, thermocouple, temperature-sensitive IC or circuit, or other suitable temperature measurement instrument and data related thereto can be transferred to controller **200** where an assessment can be made consistent with the above discussion. The temperature measurement need not be of detector **100** itself, and could be of housing **10**, of internal cavity **60**, or of another portion of dosimeter **1** or the environment surrounding dosimeter **1**. For at least this reason, cooling or insulating detector **100** from heat can provide a way to reduce power consumption by reducing the dark current.

[0057] The frame readout rate could also be controlled through the use of an analog to digital converter (ADC) with one or more thresholds. An ADC operates by converting the charge in each pixel into a digital number to be used by controller **200** to determine whether an ionizing event has been observed in that pixel. 8, 12, 16, 18 or 24-bit converters are commonly used in cameras and are readily available for use in the dosimeter described

herein. In general, the more the number of bits and the more precise the converter, the faster the converter needs to operate, and the higher the power consumption. In one embodiment, which constitutes the simplest and thus potentially lowest power converter, a single level sensor, or 1-bit ADC is used. The output of such an ADC is a “1” if the charge is above a threshold and a “0” if the charge is below a threshold. A 1-bit ADC can be used to detect the presence of an ionizing event by setting the threshold at a level above the expected dark current level. If the threshold is met in one or more pixels, the ADC can assume that an ionizing event was observed in those pixel(s). A high threshold allows for a lower readout rate to be used since it is less sensitive to dark current charge accumulation. However, if the threshold is set too high, it is possible to overlook ionizing events that may fall below the threshold. In some embodiments, the threshold is set between 5% and 50% or between 5% and 25%, such as 10%, of the maximum pixel charge capacity.

[0058] In another embodiment, the ADC may have two thresholds, one near the low end of the charge measurement range, for example in the range of 5-15%, such as about 10%, of the maximum pixel charge capacity, and the other higher up, for example in the range of 30-60% of the maximum pixel charge capacity, such as at about 50%. An illustration of this is shown in **FIGS. 6A** and **6B**. This may be accomplished through the use of two level detectors, such as two comparators each operating at a separate threshold, or a single detector, such as a 2-bit ADC. The lower threshold can be used by controller **200** to adaptively adjust the frame readout rate to, for example, maintain approximately half of the pixels above the lower threshold and the other half below the threshold based on dark current alone, so that the mean of all of the pixels’ dark current is at or about the threshold level. Accordingly, in this embodiment, approximately half of the pixel dark currents will be reported as 0s and the other half will be reported as 1s in relation to the lower threshold. Other ratios and percentages, such as those between where 20% of the pixels are above the threshold and 80% of the pixels are below the threshold and where 80% of the pixels are above the threshold and 20% of the pixels are below the threshold, may be used. This configuration allows for a lower readout rate given the temperature and the other leakage determining characteristics of detector **100** while maintaining the ability of detector **100** to quickly recognize and respond to ionizing events.

[0059] **FIGS. 6A** and **6B** are basic charge versus time plots for a system using a first ADC at a higher level and a second ADC at a lower level. Consistent with the discussion above, the first ADC can detect an ionizing event while the second ADC can monitor dark current. **FIG. 6A** is labeled as “low leakage” because it represents a situation where the dark current

is low, meaning that frame reset can occur less frequently. On the other hand, in the “high leakage” situation of **FIG. 6B**, frame reset occurs more frequently.

[0060] Further with respect to this embodiment, the upper threshold can be used to differentiate an ionizing radiation event, which would cause the upper threshold to be exceeded, from charge accumulated due to dark current, which, with an appropriate readout rate, would alone be insufficient to reach the upper threshold in the absence of an ionizing radiation event. The upper threshold should be set high enough so that effectively no pixels will have a dark current above that threshold to avoid the false appearance of an ionizing radiation event. If there is a pixel or a few pixels that are consistently or often above that threshold even though the desired dark current ratio is maintained at the lower threshold for the majority of the pixels, which could be caused by unreasonably high dark current coming from local defects or impurities, then controller **200** can remember or tag that pixel or pixels as faulty and ignore their signal in determining dose. In another embodiment, the thresholds may be adjusted or be varied from pixel to pixel or over groups or subsets of pixels using a value set and stored in memory associated with dosimeter **1** based on previously measured properties of the appropriate pixel or pixels. In another aspect, a 1- or 2-bit analysis can be applied to every pixel, and if the threshold is passed so as to indicate a radiation event in that pixel, the charge or voltage may be measured with a multi-bit ADC to assess the amount of charge in the pixel above its normal background. Similarly, a test can be done with a high dose rate of ionizing photons to determine whether there are pixels that never or only rarely show an ionizing photon, or show an unreasonably low ionizing photon rate. Such pixels can also be remembered by controller **200** as faulty and not be counted in determining dose sensitivity. In the event that significant fractions of or entire rows and/or columns of pixels are determined to be faulty, those rows and/or columns can be ignored entirely.

[0061] Another embodiment uses a multi-level threshold ADC at the lower level to sense and monitor dark current. This allows for a more rapid and nuanced control of frame readout rate as a function of dark current and as dark current changes. Two or three thresholds can be accommodated as a 2-bit ADC. For example, the thresholds could be set at 8%, 10%, and 12% of pixel capacity. Four to seven thresholds can be accommodated as a 3-bit ADC. In another embodiment, the upper threshold is a multi-bit ADC. This allows some assessment of ionizing photon deposited energy, such as in the form of pulse height discrimination or blooming comparisons. For example, the upper thresholds can be set at 30%, 50%, and 70% of maximum pixel charge capacity. In another embodiment, both the lower and the upper thresholds or regions are 2 or more bit ADCs, which may have different threshold increments

or steps. In each of these embodiments, the thresholds can be customizable for a pixel or group of pixels to allow for further refinement of the operation of detector **100**. In addition, a higher precision (and likely higher power consumption) ADC can be used only for those pixels which meet a certain threshold, such as one or more of the higher thresholds.

[0062] The characteristics of detector **100**, such as sensitivity and pixel size, are not limited and can depend on numerous factors, including the environment in which detector **100** is intended to be used, cost, and others. Upon reading this disclosure, one of skill in the art would be capable of selecting a detector **100** with the appropriate characteristics.

[0063] For instance, the overall sensitivity of detector **100** in counts per minute (CMP) per microSievert per hour ($\mu\text{Sv/hr}$) can itself depend upon many factors. One primary factor is the size of the sensitive area of detector **100**. Commercially available camera chips are commonly comprised of a sensitive area that is about 5mm on a side, 1 cm on a side, or 1 inch (2.54 cm) on a side, with the form factor and ratio of height to width determined by the desired format of the image. Another significant factor that can affect sensitivity is the material from which detector **100** is made and its interaction characteristics for the radiation in question as well as its band gap. Yet another factor is the presence of absorbing materials around detector **100** which can absorb or scatter the radiation before it reaches detector **100**. Similarly, material around detector **100** can increase detector sensitivity by scattering radiation to detector **100** or creating delta rays which reach detector **100**. Some materials, such as scintillators, can absorb the radiation and emit light which is converted into charge by detector **100**.

[0064] By way of example, in an article titled, "Smartphone radiation detector app tests positive," published on June 30, 2014 on the website phys.org, the cameras of an Apple iPhone 4S and a Samsung Galaxy S2 were used as radiation detectors. It is noted that these cameras did not implement any of the inventive features described herein. The sensitivity was reported as approximately 100 counts per minute (CPM) at a dose of 20 micro-Sieverts per hour ($\mu\text{Sv/hr}$), with the Galaxy having about twice the sensitivity of the iPhone. In some jurisdictions, the limit on radiation exposure for an unrestricted area is 20 $\mu\text{Sv/hr}$, in which case the detectors in those phones discussed in the article referenced above would provide 100 counts per minute or about 1.5 counts every second. By way of comparison, the commercially available RaySafe™ personal dosimeter product indicates green until 200 $\mu\text{Sv/hr}$, which for the detectors in the phones discussed above would correspond to 1000 CPM. Accordingly, sizing detector **100** to be approximately the size of the detectors in the phones discussed above would provide sufficient sensitivity.

[0065] Regarding pixel size and dark current, by way of example, the dark current for a commercially available Hamamatsu S2387 series photodiode is reported to be about 8^{-13} A/mm² at 25°C and 8^{-12} A/mm² at 60°C in the Hamamatsu Photodiode Technical Information booklet. In one embodiment, detector **100** may use a 1 cm² detector with 1000 pixels in each direction. In such a detector, each pixel in that detector is approximate 10 μm on a side. The leakage current for such a pixel is about 8^{-17} A at 25°C and 8^{-16} A at 60°C. A 10 keV X-ray photon, assuming it is all absorbed in such a pixel would create about 2700 charges almost instantaneously in the pixel because, for silicon, one electron-hole pair is created for every 3.7eV of deposited energy. Thus, if the threshold for an ionizing event is set to be 5 times that of the average leakage current, each pixel in the detector would need to be read or refreshed at a rate of once every 1.1 seconds at 25°C and once every 0.11 seconds at 60°C.

[0066] In an embodiment utilizing smaller pixels, the required readout rate decreases proportionally to the pixel area reduction, but the number of pixels increases proportionally to the same, so the number of pixels read per unit time remains approximately the same. Further, if power consumption is proportional to the number of pixels read per unit time, to a first order, reducing pixel size may not further decrease power consumption. To a first order, the smaller the pixel, the lower the capacitance of the pixel. However, the exact capacitance depends on various factors, including the type of circuit, for example CCD, CMOS or DRAM, and the specific process properties, for example line widths, gate thicknesses, diffusion depths and a myriad of additional factors. In certain embodiments, a pixel with a capacitance small enough to reliably measure a charge on the order of 2700 charges is sufficiently small.

[0067] Another factor which can be used by controller **200** to adjust readout mode, including frame readout rate, is the rate at which ionizing radiation events are received by detector **100**. In a low radiation dose rate environment, the readout mode can include a frame readout rate that is kept as low as possible using an extended readout mode, and the readout mode can optionally employ a frame segment readout mode to improve response time at very low frame rates, as described herein. As the dose rate increases, the frame readout rate may be increased to keep below an acceptable level the probability of having two radiation photons strike a single pixel or pixels and thus be confused as one larger ionization event, resulting in an underreporting of the dose received. This is commonly called pulse pile-up, and the frequency of its occurrence can be reduced by increasing the frame readout rate as the dose rate increases. Thus, by having a range of frame rates being quickly selectable or controllable by controller **200**, such as a range of available readout rates from 30 frames per

second to 1 frame per minute, and including many pixels in detector **100**, for example 500,000 to three million, a very large range of dose rates can be accommodated without significant effect or degradation from pulse pile-up.

[0068] In an additional embodiment, if at the highest frame readout rate, the count rate becomes sufficiently high, controller **200** may, with reasonable accuracy, correct the dose rate reading to account or compensate for the pulse pile-up that has occurred. This is possible, in part, because pulse pile-up is a statistical event. Controller **200** could also perform a blooming assessment and perform blooming compensation if blooming is determined. Anti-blooming features are known in the art.

[0069] In another embodiment, if controller **200** senses a high dose rate, only a segment of detector **100** is read at a higher frame readout rate to scale the dose and reduce pulse pile up. The remainder of detector **100** is not read at all so the pixels “fill up” with leakage. For instance, one-tenth of the pixels could be read at a frame rate that is 10 times the normal frame rate. Effectively, the frame size is reduced or the frame of use may be considered to be a segment of the maximum possible frame. By way of a further example, if the entire detector **100** can be read at a maximum of 30 frames per second, then half could be read at 60 frames per second and one quarter could be read at 120 frames per second. Controller **200** would adjust the relationship of counts to dose to reflect the area actually read so that the effective dose received by the detector is correct. For example, if only 10% of the total area of the detector is read, the ratio of dose over counts would be increased by a factor of 10. This may be termed segment or segmental readout mode. Once the high dose rate situation ends, controller **200** may return to a readout mode in which the whole frame is read, and may discard the initial charge or information from the first readout of the pixels that had not been refreshing during the segment readout mode period.

[0070] In an additional embodiment, rather than reading a whole frame at a time, the readout mode involves reading a segment consisting of one row or a group of rows and processing the counts in the segment as a unit. This is another example of segment readout mode and can occur regardless of whether a high dose rate is sensed. For example, if detector **100** is 600 rows by 800 columns, and the frame readout rate is one frame per minute, then there is a one minute gap between readout status changes because that is the time between frame data acquisitions by controller **200**. However, it may be desirable that data is received in increments that are less than one minute, for example one second, in order to ensure the period of time between which some readout is made does not exceed a maximum time threshold. For example, the ability of dosimeter **1** to quickly respond to a high dose rate

or other potentially harmful ionizing event, such as by initiating an alarm, is dependent upon dose information being received at reasonably frequent intervals. Thus, this maximum time threshold between frame data acquisitions can be referred to as an alarm determination period as it reflects the responsiveness of dosimeter **1** to an ionizing event. In this embodiment, by way of example, the rows could be read ten at a time, starting every second to read a new set of ten rows. Thus, in one minute, the whole frame is read out, but there is a new set of data available every second. As mentioned, the benefit of this approach is that, if a significant dose rate is suddenly encountered, enough pixels are being sampled every second that if the dose rate is high enough, controller **200** can trigger an alarm with minimal delay. In addition, controller **200** can more rapidly respond to an increased dose rate by increasing the frame readout rate to avoid or reduce any pulse pile up and/or confirm the increase in dose rate that would have occurred if controller **200** waited until the next full readout cycle to increase the frame readout rate. Optionally, the size of the segment may be selected by controller **200** to adapt to the desired alarm determination period.

[0071] By way of another example, the temperature of detector **100** can be kept low, such as by exposing detector **100** to a cooling source such as air or fluid. As discussed above, dark current is temperature dependent and, by decreasing the temperature, the amount of dark current can also be reduced.

[0072] Consistent with the description above, several readout modes may be utilized. For example, a normal or simple readout mode can involve the controller **200** reading out a whole frame, including every pixel, at the designed frame rate, generally providing for every pixel to be read each 1/30th or 1/60th of a second. High speed integrated circuits and controllers may allow for every pixel to be read every 1/1000th of a second.

[0073] It may be desirable to slow down the readout rate in this embodiment to conserve power or achieve other benefits as mentioned herein. There are multiple readout modes which can be utilized, either separately or in combination, to achieve this. For example, an extended readout mode can slow the row to row readout rate so that reading a whole frame takes longer, for example 1/10th of a second or a whole second. This can allow for the dynamic, optimal adjusting of the readout rate to the dark current. The readout of each pixel in a row may occur at the normal high rate with a pause between row readouts, or the readout of each pixel may be proportionally slowed, depending upon the specific design and circuit implementations used.

[0074] As also discussed above, segment readout mode can involve reading the pixels in a segment of the frame as a set, such as a set of one or more rows, for example 1/60th of the

whole frame, with a pause before moving on to the next segment. The whole frame can be read before starting over. This mode can provide more rapid estimates of the occurrence of an increased dose rate and can be utilized in conjunction with or as an alternative to an extended readout mode, such as if the integrated circuit is not capable of extended readout mode, for example where the whole frame readout time would preferably be one minute due to a low leakage current situation but it is desirable to provide a warning to the user if the radiation situation changes in a time shorter than a full minute. By using segmental reading with a segment read every second, controller **200** could alert the user within a second if an alarm situation was occurring. For example, reading a segment of 1/60th of the frame every second would enable a total frame readout rate of once per minute and a response to the user every second.

[0075] In a variation of the segment readout mode, referred to herein as the partial readout mode, one part of the frame is read repeatedly while the other parts of the frame are ignored or not read, thus collecting data from only a portion of the frame. This mode effectively reduces the sensitivity proportionally to the fraction of the overall detector area that is not read. This mode may be used, for example, when encountering high dose rates so as to avoid pulse pile-up and inaccurate readings. In a high dose rate situation, sacrificing sensitivity for accuracy may be the appropriate trade off to avoid pulse pile-up and saturation. In the partial readout mode, the conversion of pulse count to dose is appropriately scaled.

[0076] Another situation where the partial readout mode may be useful is in the case of ultra-high temperatures where the whole frame readout may not be fast enough to compensate for the high dark current or would result in the use of an unacceptably large amount of power. In this case, controller **200** may select to read a partial frame and adjust the sensitivity accordingly.

[0077] Various combinations of the different readout modes may be useful and are within the scope of the present disclosure.

[0078] In some embodiments, dosimeter **1** may include one or more radiation and energy compensation features to control or adjust the energy that is incident on detector **100**. Compensation can improve the ability of detector **100** to accurately report the effect of the various radiation or photons by accounting for differences in response between the detector and human tissue. In one embodiment, the energy compensation feature is in the form of a tissue equivalent plastic that is used to form all or a portion of housing **10** and/or detector **100**. In another embodiment, one or more filters **90** may be placed over all or select sections of detector **100**, as illustrated in **FIGS. 5A-D**. The material of filters **90** can be selected so as

to compensate for the difference in the response of detector **100** to photons of different energies to the response of human tissue to the same photons. Non-limiting examples of filter materials include aluminum, copper, tin, and plastic. Combinations of filter materials can be used in the same filter **90**, and combinations of multiple filters **90** can also be used.

[0079] With reference to **FIGS. 5A-B**, one embodiment includes a filter **90** arranged in a pattern that fits fully within the sensitive area **170** of detector **100** with some clearance or gap around the outer edges so that slight misalignments or shifts in the placement of the filter **90** will not cause it to move off the sensitive area **170** and ensure sensitive area **170** remains covered by filter **90**. With reference to **FIG. 5C**, an alternative embodiment uses linear filter elements **92** which extend past two opposite edges of the sensitive area **170** and include clearance to the other two opposite edges of sensitive area **170**. The linear filter elements **92** may be cylindrical filters. This provides a similar mismatch or mis-positioning tolerance to the placement of filter **90**. With reference to **FIG. 5D**, in another embodiment, a round filter **94** can be used to improve the angle independence. All filter elements **90**, **92**, **94** can be relatively flat filters or they may extend out of the imager plane in the z-direction, including in a “humped,” “cylindrical,” or “domed” configuration.

[0080] Filters **90** can cover both front face **150** and back face of detector **100**. In one embodiment, the same filter material is used for filters **90** on both front face **150** and back face of detector **100** to ensure that photons incident on detector **100** from either direction pass through the same filter material. Alternatively, the filter material can vary as between the front **150** and back face of detector **100**, and at least one of front **150** and back face can have no filter at all.

[0081] In an embodiment where individual rows or groups of rows are read and acted upon as described in some embodiments herein, for example extended readout, frame segment readout, or partial frame readout, there may be additional benefit to this aspect with the filters traversing, generally orthogonal to, or otherwise equivalently uniform with respect to, the readout direction in that the proportional effects of the filters on dose accuracy are preserved and do not vary with or depend upon segment(s) being read out or the readout mode. Filter **90** can be generally perpendicular or orthogonal to the rows, meaning that each row or minimal segment has pixels under the filter **90** to provide for correct segmental energy response. This arrangement is beneficial because decisions to increase the frame readout rate can be made after the reading of each row or group of rows, and if, for example, the filter material was more absorbing over some whole rows than other whole rows, the responsiveness of detector **100** and, for example, issuance of an alarm due to observance of a

high dose rate, could be delayed because of the increased absorption. Of course, other patterns in addition to a linear arrangement can provide this orthogonality, including, for example, a diagonal, checkerboard, or pseudorandom pattern. Filter gradients can also be used, either through the use of a single graded filter or through the arrangement of multiple adjacent or overlapping filters, and the frame readout can optionally be run in a direction perpendicular to the filter gradient.

[0082] In an additional embodiment, scintillators or phosphors may be optically coupled to one or more pixels to increase sensitivity and/or linearity of energy response.

[0083] One skilled in the art would understand that a variety of combinations of materials, thicknesses of the materials, and areas of materials can be selected to achieve sufficient energy compensation. It would also be understood by those skilled in the art that different materials will be more absorbent of radiation than would be a gap or air. It would also be understood by those skilled in the art that the specific absorbers may be included, for example to provide or increase sensitivity to neutrons.

[0084] In other non-limiting embodiments, a rough photon energy analysis can be conducted by controller **200** to allow for after-the-fact energy compensation. This analysis may be done in combination with, or as an alternative to, a physical energy compensation feature, such as the filters, scintillators, and tissue equivalent plastic discussed above.

[0085] Dosimeter **1** can also include one or more fault detection features to determine correct operation of or identify faults within detector **100**. Data collected from defective pixels can be set aside or, if the fault is extensive, the user can be alerted to the fact that dosimeter **1** is or is not operating properly, such as through an alarm. Mechanisms to detect faulty pixels based on the use of thresholds are discussed above and constitute one such fault detection feature. Another fault detection feature includes using a temperature sensor, such as those discussed above, to measure the temperature of detector **100** and programming controller **200** to compare the measured dark current with the dark current expected for the measured temperature of detector **100**. Another fault detection feature involves comparing the total dose rate to what is possible or reasonable given the normal background level to see whether the total dose rate falls below what is possible or reasonable to expect. Yet another embodiment of a fault detection feature involves assessing the time between successive ionizing photon detections and assigning a fault condition if the time between two or more pulses is above a threshold. In yet another embodiment, two or more independent detectors are used and controller **200** or an external system makes a comparison between the photon detection rates of the two detectors. This embodiment provides the added benefit that, should

one detector be deemed to be faulty or otherwise fail, dosimeter **1** can continue to operate with the non-faulty detector(s). Optionally, the two image sensors can be faced in different directions, such as with a 90 degree orientation angle between them or facing in opposite directions, to improve the angular uniformity of response. In a related embodiment, a single detector containing two or more image sensors and associated readout electronics can be included, so that the redundancy and fault checking includes additional system aspects. Optionally, controller **200** may make a similar comparison between two halves or other segments of a single detector since the response over the segments should be roughly equal. All of the fault detection features described above can be performed by controller **200** based on data received from detector **100** or pre-programmed into controller **200**.

[0086] As with all electronic circuits there is the possibility that dosimeter **1** could fail due to, for example, loss of connection to power or damage such as cracking of the detector **100** itself. To ensure radiation dose exposure is continued to be measured in such a situation, one or more passive dosimeter devices can be coupled and used in combination with dosimeter **1**, either as a separate device or as an integral component of dosimeter **1**. Such passive dosimeter devices are known to those skilled in the art and include, for example, film, a thermoluminescent (TLD) material, or an optically stimulated luminescence (OSL) material. The passive dosimeter device can be read periodically, such as yearly or only in the case of failure of dosimeter **1**. Optionally, the passive devices could include electronic readout capability. Non-limiting examples include those detectors that are used in the INSTADOSE™ product from Mirion Technologies, Inc. and generally described, for example, in United States Patent Application Publication No. 2013/0334432 and associated patents, and the VERIFI™ product being developed by Landauer, Inc., as generally described in International Patent Application Publication No. WO 2016/059504A1 and associated patents. Each of these documents is incorporated herein by reference.

[0087] Depending on the intended environment of use, it may also be desirable to select the components of dosimeter **1** such that many orders of magnitude in dose rate can be covered. A significant range of magnitudes of total dose can be covered, for example, by the use of a digital circuit where individual ionizing photons are detected and counted digitally, with the maximum count being effectively unlimited. For example, a 36-bit counter can record up to 10^{56} photos.

[0088] As described, controller **200** can receive signals from detector **100** and communicate control signals to detector **100**. Controller **200** can include, but is not limited to, a processor such as a microcontroller, microprocessor, or other type of computing device.

Controller **200** may have stored thereon, or be in communication with, program instructions that, when executed by controller **200**, cause controller **200** to perform data processing tasks, including dynamically adjusting the readout mode. For example, a computer-readable medium may be located on or in communication with controller **200** for storing the program instructions. In non-limiting configurations, controller **200** could also be divided among a plurality of processors in communication with one another, for example, controller **200** could be divided into two segments, one in housing **10** of dosimeter **1** and one located external to housing **10**. In some non-limiting embodiments, controller **200** is programmed to slow down its own processing speed when the frame readout rate is slowed or to operate in bursts when data is available.

[0089] In addition to those processes discussed elsewhere, controller **200** can be configured to perform various processing tasks related to the function of dosimeter **1** including, but not limited to, converting pixel charge into radiation dose; counting pulses and determining the number of pixels above and below a threshold; summing/integrating charge that is above a dark current threshold; and operating in a multi-channel analyzer mode to perform quality factor analysis and energy compensation. Controller **200** can also be configured to perform multi-pixel processing, such as determining whether an observed charge in adjacent pixels is caused by a single ionizing event, and event distribution analysis to account for lost charge, including increasing peak height.

[0090] Dosimeter **1** can also include a user interface **80**. User interface **80** can provide an alarm to alert a user of one or more conditions through, for example, sound, voice, light, or vibration. For example, user interface **80** can alert the user through a tactile, visual, or audible alarm if an abnormally high dose rate has been received. User interface **80** can also provide information to the user through, for example, various screen displays (if the dosimeter **1** includes a screen) of text, status bars or meters (including the power remaining in power source **300**), or lights, or through LEDs or other suitable indicators. User interface **80** can also include one or more buttons to receive information from the user. Information can also be provided by the user through voice and/or motion, such as voice commands or shaking dosimeter **1**. User interface **80** can be controlled by controller **200**. A non-limiting example of user interface **80** is illustrated in **FIG. 1** as a set of LEDs.

[0091] In certain non-limiting embodiments, power source **300** can include one or more batteries, such as conventional carbon zinc, alkaline, or lithium batteries which are well known and widely available. The batteries can be rechargeable or finite life batteries. Power source **300** can be replaceable or can be integral with and/or permanently affixed to dosimeter

1, such as by forming housing **10** in a manner that does not allow access to power source **300** without destroying housing **10**. A non-replaceable, non-rechargeable power source **300** provides the added benefit of setting a finite life for dosimeter **1**. This can help ensure dosimeter **1** is not used past its calibration period. It can also provide a future revenue stream through the purchase of replacement dosimeters as well as a mechanism for the periodic review of whether the user has a fully functional dosimeter. In one embodiment, power source **300** has sufficient capacity to power dosimeter **1** for between approximately 6 and 14 months, such as about 12 months. Alternative power sources can also be used either in place of the battery or in combination with the battery. For example, solar powered dosimeters can be used for applications where dosimeter **1** is frequently exposed to solar radiation or even lights within a facility. In some embodiments, power source **300** may be partitioned. For example one power source may be operating dosimeter **1** and a second power source operating communication and alarm functions. This helps to ensure that dosimeter **1** will continue to function and accumulate dose even if the power to the display or the external communication is drawn down and not yet replaced.

[0092] In some non-limiting embodiments, dosimeter **1** is capable of communicating with an external system through either a wireless communication protocol, such as RFID or Bluetooth, or through wired communication when dosimeter **1** is connected to an external device through a cable or docking station. Data from dosimeter **1** can be transferred to the external system, such as a computer, for further processing, storage, and analysis.

[0093] With reference to **FIG. 7**, in one embodiment, the external system can form at least part of a radiation management system **1000**. Radiation management system **1000** can receive data about ionizing radiation dose from one or more dosimeters and store this information in a database record associated with a user or group of users. The database record could include information about the user's historical radiation exposure, including environmental exposure as collected by one or more dosimeters as well as exposure from more focused events such as radiation from an X-ray or other procedure involving medical imaging and/or radiopharmaceuticals. To this end, system **1000** could be in communication with one or more medical facilities so as to receive information about a user's radiation exposure that may have occurred in these facilities, whether as a patient and/or a worker. These facilities may have dosimeters (including one or more dosimeters like those discussed herein) embedded in the bed of the imager on which the patient rests when receiving radiation. System **1000** could also compile information from multiple dosimeters associated with the user. As mentioned, dosimeter **1** may have a finite life. Thus, radiation management

system **1000** can be used to track radiation exposure over successive dosimeters. In addition, some users may carry multiple dosimeters. For example, the user may carry a first dosimeter while at work and carry a second dosimeter while outside of work. The radiation management system **1000** could combine the radiation reported from each dosimeter **1**, as well as other sources (e.g., medical procedures in hospitals), to provide a total radiation history for the user. Optionally, dosimeter **1** could be informed automatically when the user is at work or elsewhere and separate the dose received accordingly into occupational dose and other dose. In this scenario, the user could be supplied with information on his/her total dose and the employer with information as to the total dose and/or the dose the user received during work for which the employer would be responsible. This differentiation may be determined based on, for example, user input, time of day, or geographic location ascertained from a GPS or location specific WiFi signal.

[0094] Radiation management system **1000** can also be used to generate reports, such as quarterly or yearly reports, on the user's radiation exposure. These reports could be accessed by the user or sent to the user periodically through the mail or electronically over the Internet. In one non-limiting embodiment, data collected by system **1000** could be presented to the user on a smartphone application ("app") that can be readily accessed by the user and can provide the user with an up-to-date account of his or her radiation exposure. The data could be updated, for example, daily, hourly, or even by the minute or effective real time.

[0095] As mentioned, information compiled by the radiation management system **1000** could be accessed by the user through the Internet or other portal, or it could be periodically sent to the user in the form of a report. In one non-limiting embodiment, radiation management system **1000** could determine whether the user is approaching a radiation exposure threshold and alert the user, such as through a message sent to the user's smartphone, that the threshold would soon be reached. Radiation management system **1000** could also alert the user if an abnormally high dose was received so that the user can take appropriate precautions, including stepping back from a source of radiation or avoiding the location where the high dose was received.

[0096] In some non-limiting embodiments, the radiation management system **1000** can receive, in addition to dose information, information about the user's location over the period of time when a radiation dose was received. This location information could be generated by a GPS device associated with the user, such as the user's smartphone, or a GPS associated with the dosimeter itself. Location information could also be discerned based on the source of the data. For example, data received from a dosimeter used at work could be reported

separately from data received from a dosimeter used outside of work. Information about the user's location when radiation events occur can be included in the user's radiation report so as to provide the user with an understanding as to the locations where the user experiences the most (and least) amount of radiation exposure.

[0097] As mentioned, radiation management system **1000** could also monitor the exposure of a group of users, such as a certain group of employees at a workplace. One such example would be the radiologist and technicians in a hospital. Radiation management system **1000** could generate reports on the group of users and provide reports to the employer who could use the reports to ensure the safety of the users. Such a report may be particularly useful if, unbeknownst to the employer, one or more employees is exposed to a high amount of radiation while outside of the workplace. In such a case, the employer can take steps to ensure workplace radiation exposure is limited for these employees. The data compiled by radiation management system **1000** may also be useful for those involved in researching the root causes of various medical conditions, such as cancer. Data on historical radiation exposure may serve as one tool to help establish epidemiologically whether there is a dose or dose rate threshold for serious radiation damage to people, e.g., cancer causation.

[0098] Although the disclosure has been described in detail for the purpose of illustration based on what is currently considered to be the most practical and preferred embodiments, it is to be understood that such detail is solely for that purpose and that the disclosure is not limited to the disclosed embodiments, but, on the contrary, is intended to cover modifications and equivalent arrangements. For example, it is to be understood that the present disclosure contemplates that, to the extent possible, one or more features of any embodiment can be combined with one or more features of any other embodiment.

THE INVENTION CLAIMED IS:

1. A dosimeter for measuring one or more doses of radiation, comprising:
a detector, wherein the detector comprises a pixelated circuit comprising readout electronics;
a power source; and
a controller in communication with the readout electronics and adapted to dynamically adjust a readout mode of the detector based on information received from the detector.
2. The dosimeter of claim 1, wherein the pixelated circuit is a light imaging circuit.
3. The dosimeter of claim 1, wherein the pixelated circuit is a CCD, CMOS, or DRAM circuit comprising a plurality of pixels.
4. The dosimeter of claim 1, wherein the controller is adapted to dynamically adjust the readout mode of the detector based on one or more measurements related to dark current.
5. The dosimeter of claim 1, wherein the controller is adapted to dynamically adjust the readout mode of the detector to reduce total power usage.
6. The dosimeter of claim 1, wherein the controller is adapted to dynamically adjust the readout mode of the detector or an operating mode of the controller based on a rate at which ionizing radiation events are detected by the detector.
7. The dosimeter of claim 1, wherein the controller is adapted to dynamically adjust the readout mode of the detector based on a fault in one or more pixels, rows, columns, or segments of the detector.
8. The dosimeter of claim 1, wherein the controller is adapted to dynamically adjust the readout mode of the detector based on a temperature associated with the detector.
9. The dosimeter of claim 1, further comprising at least one filter positioned over the detector.

10. The dosimeter of claim 9, wherein a first filter is positioned over a front face of the detector and a second filter is positioned over a rear face of the detector, wherein the rear face is opposite the front face.

11. The dosimeter of claim 10, wherein the first filter and the second filter are comprised of the same filter material.

12. The dosimeter of claim 9, wherein the at least one filter is arranged so that each segment of the detector has the same effective filtering.

13. A method of measuring one or more doses of radiation using a dosimeter, wherein the dosimeter comprises a detector comprising a pixelated circuit with readout electronics, a power source, and a controller, comprising:

receiving, at the detector, one or more ionizing radiation photons;

transmitting information about the one or more ionizing radiation photons to the controller; and

dynamically adjusting, by the controller, a readout mode of the detector based on the information received about the one or more ionizing radiation photons.

14. The method of claim 13, further comprising receiving, at the controller, one or more measurements related to dark current.

15. The method of claim 14, wherein the controller dynamically adjusts the readout mode of the detector based on the one or more measurements related to dark current.

16. The method of claim 15, wherein the controller decreases the readout rate of the detector based on the one or more measurements related to dark current.

17. The method of claim 15, wherein the controller increases the readout rate of the detector based on the one or more measurements related to dark current.

18. The method of claim 13, wherein the controller dynamically adjusts the readout mode of the detector based on a rate at which the ionizing radiation events are detected by the detector.

19. The method of claim 18, wherein the controller increases the readout rate of the detector, decreases the readout area of the detector, or both increases the readout rate and

decreases the readout area of the detector if the rate at which the ionizing radiation events are detected by the detector is above a threshold level.

20. The method of claim 13, further comprising measuring a temperature associated with the detector and dynamically adjusting, by the controller, the readout mode of the detector based on the temperature associated with the detector.

21. The method of claim 13, further comprising initiating an alarm if a rate at which the ionizing radiation events are received by the detector exceeds a threshold level.

22. The method of claim 13, further comprising initiating an alarm if a total radiation dose received by the detector over a period of time exceeds a threshold level.

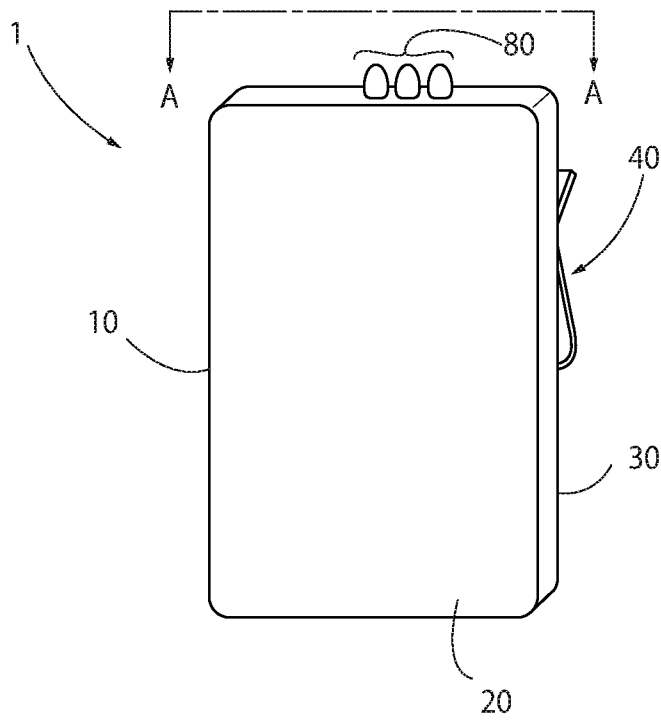


FIG. 1

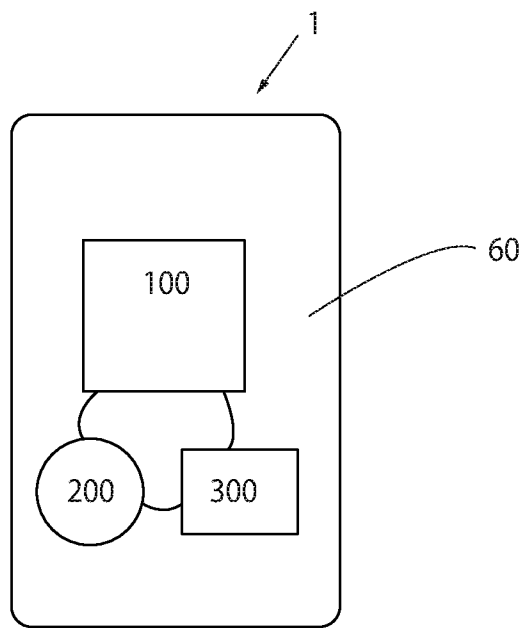


FIG. 2

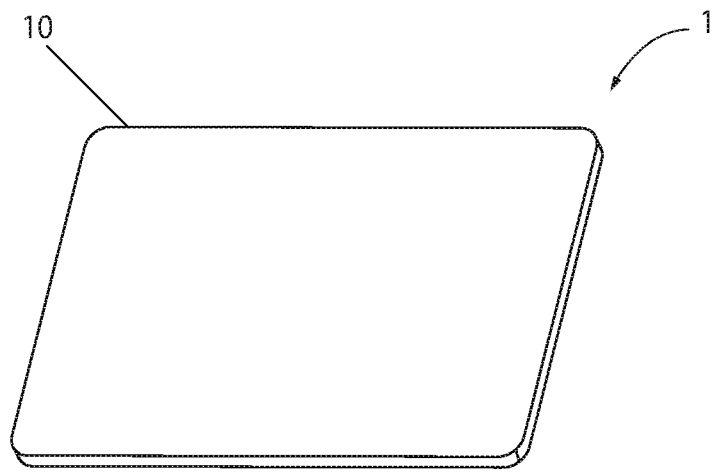


FIG. 3

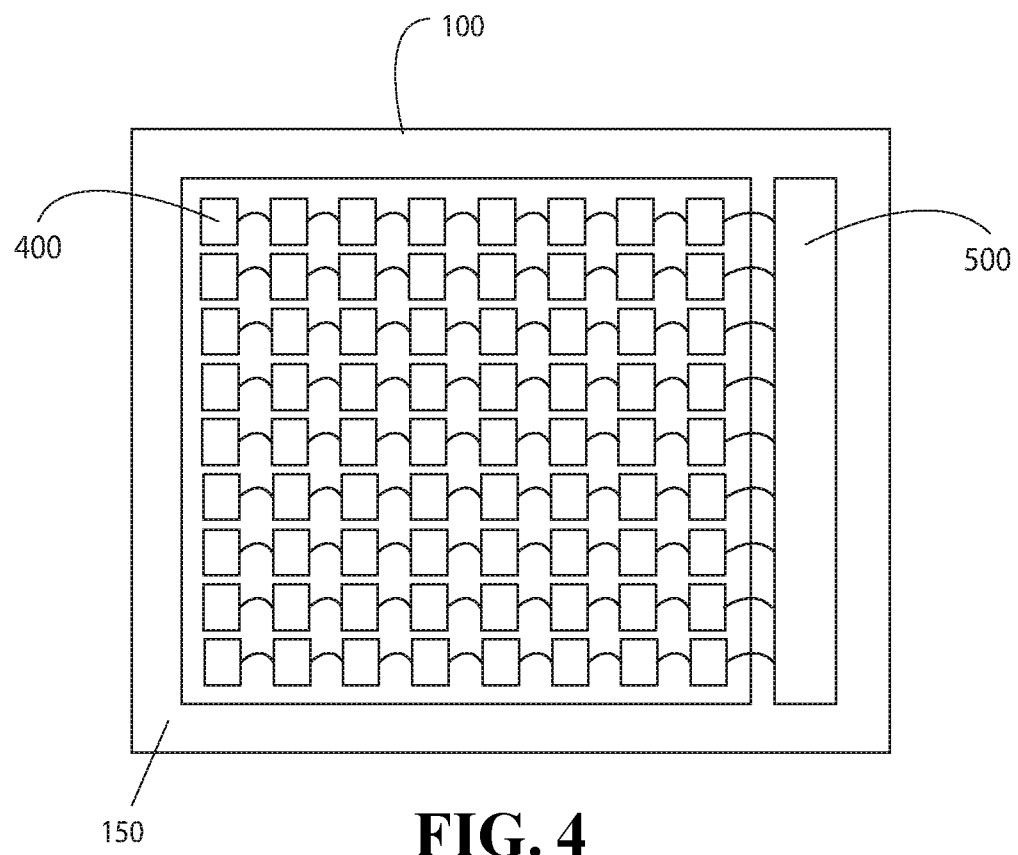


FIG. 4

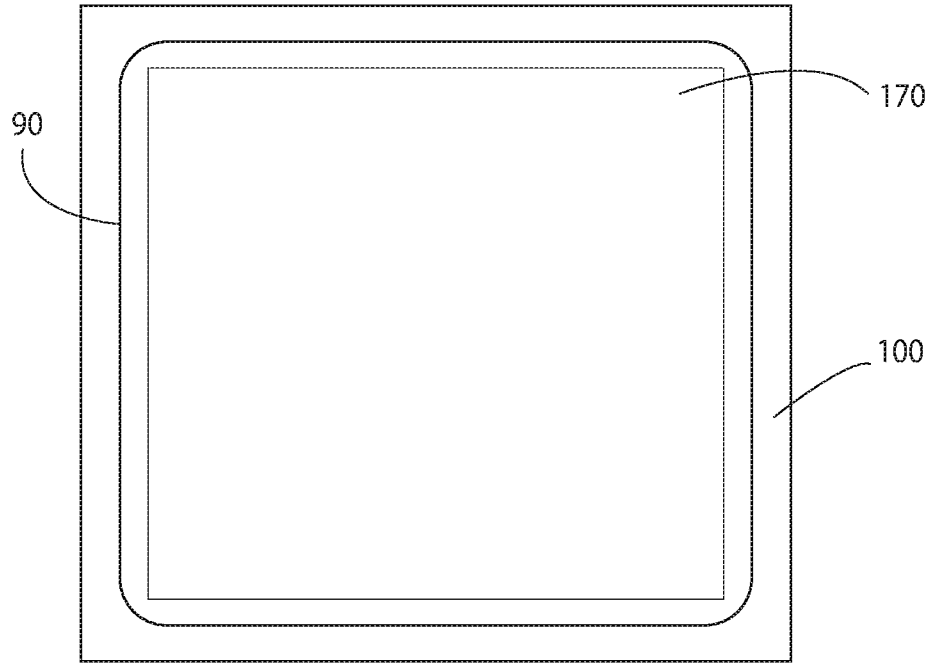


FIG. 5A

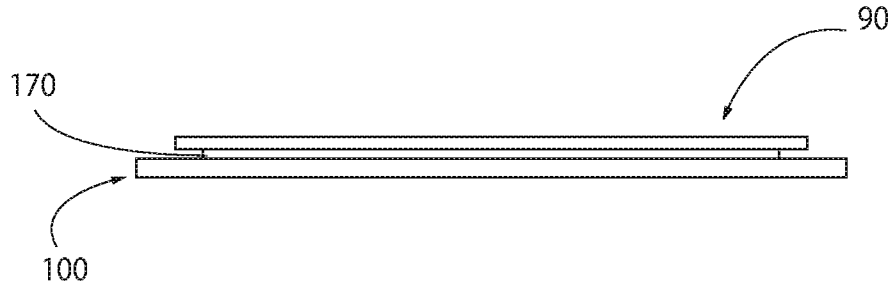


FIG. 5B

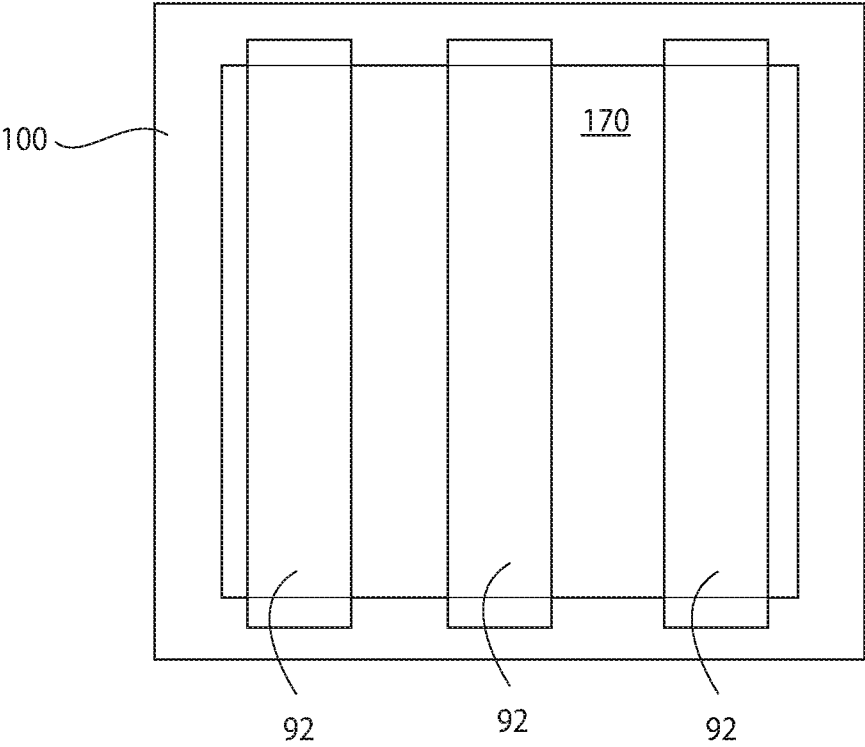


FIG. 5C

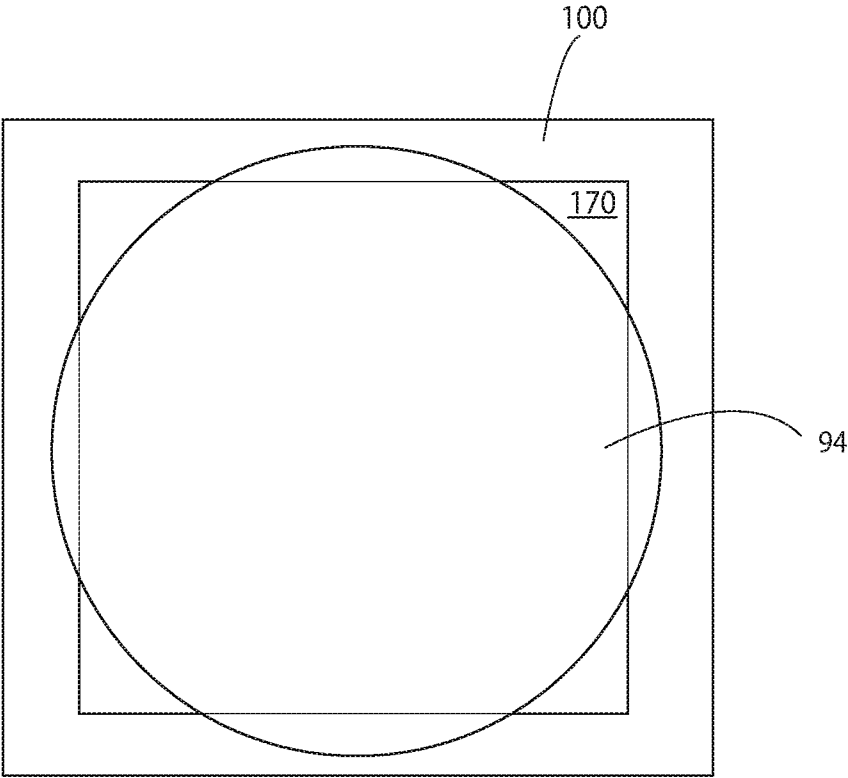
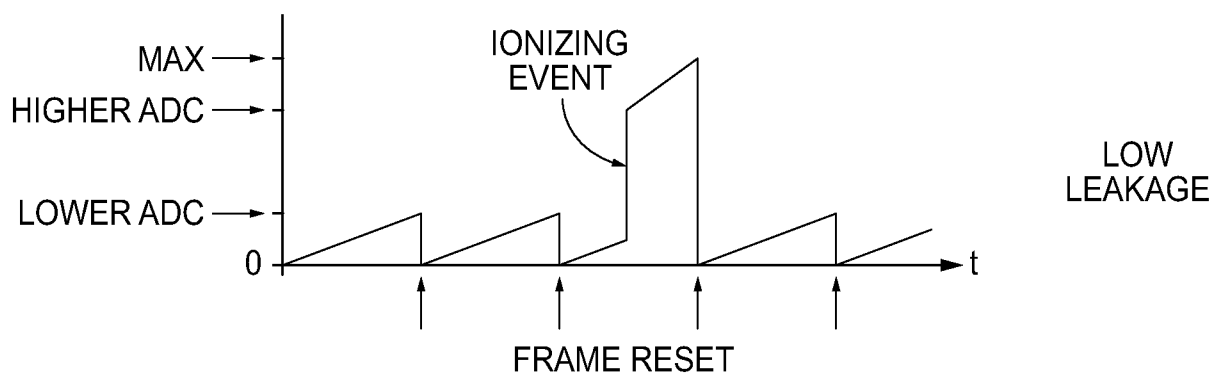
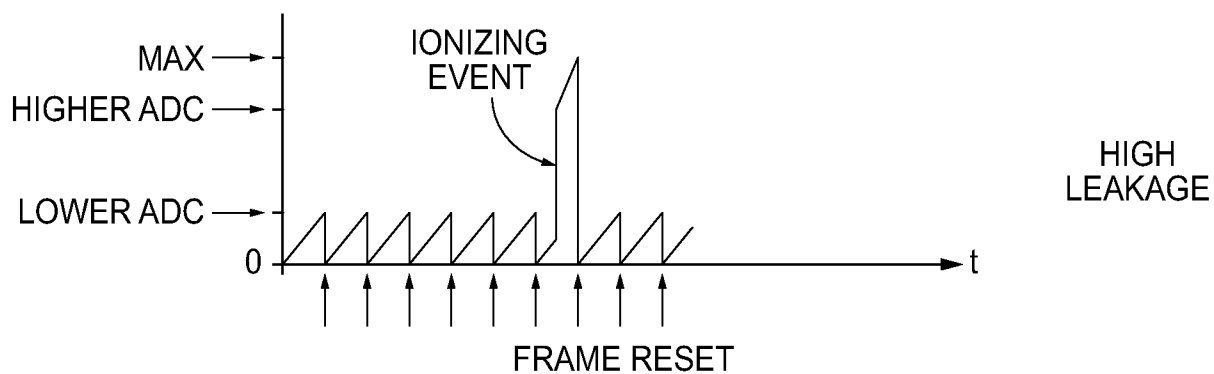


FIG. 5D

**FIG. 6A****FIG. 6B**

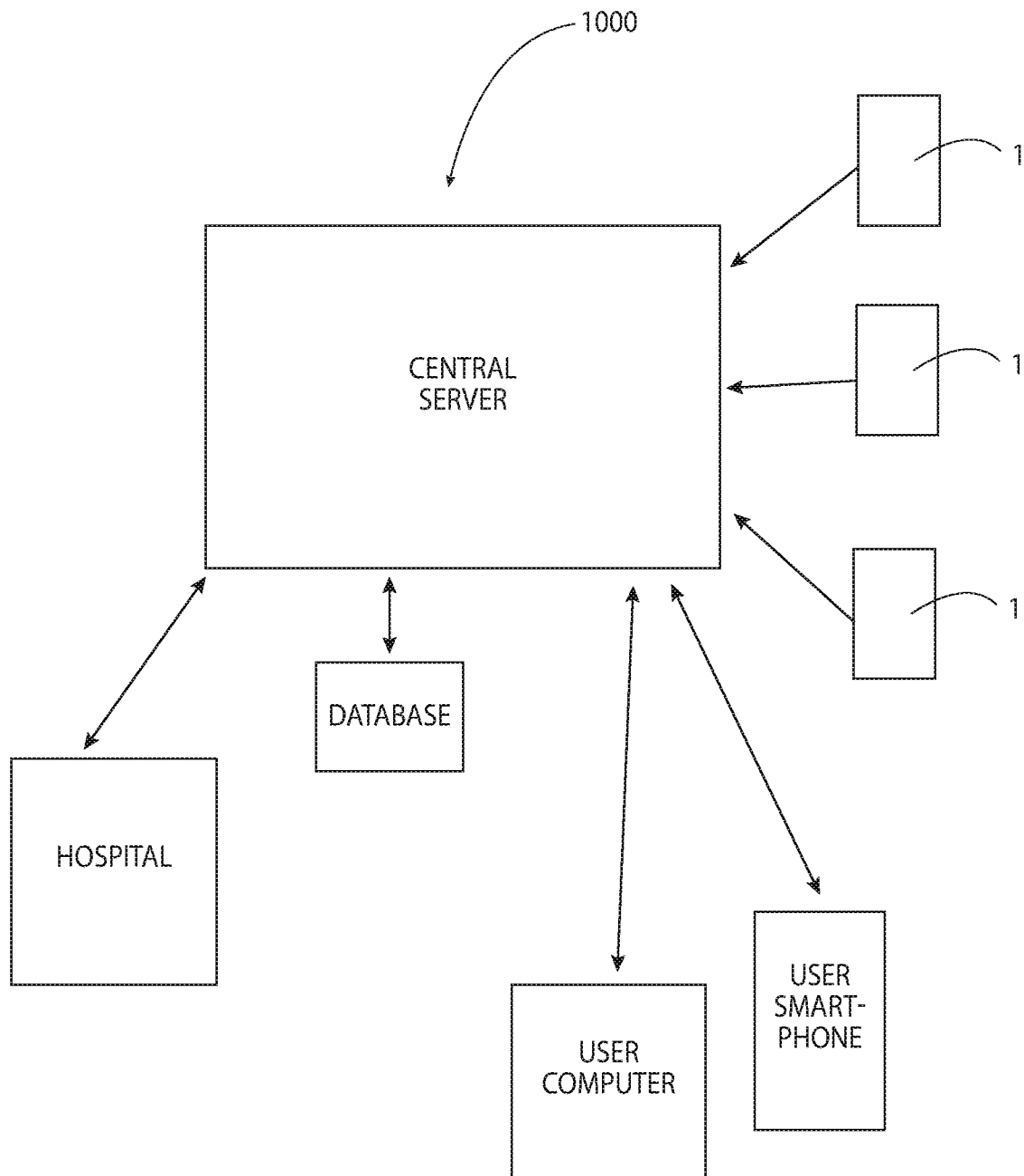


FIG. 7

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2016/052647

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - G01T 1/02; G01T 1/24; G01T 1/178 (2016.01)

CPC - G01T 1/026; G01T 1/24; G01T 1/2928 (2016.11)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC - G01T 1/02; G01T 1/24; G01T 1/178

CPC - G01T 1/026; G01T 1/24; G01T 1/2928

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

USPC- 250/370.01, 370.07, 370.08, 370.14; 340/539.22, 539.29 (keyword delimited)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

Orbit, Google Patents, Google Scholar

Search terms used: dosimeter, radiation, detector, pixels, CCD, controller, battery, readout, filters, temperature, defective, dose rate

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2007/0075251 A1 (DOUGHTY et al) 05 April 2007 (05.04.2007) entire document	1-3, 5, 6, 8, 13, 18-22
Y		4, 7, 9-12, 14-17
Y	US 2013/0182823 A1 (FUJIFILM CORPORATION et al) 18 July 2013 (18.07.2013) entire document	4, 7, 14-17
Y	US 2010/0302533 A1 (FEHRENBACHER et al) 02 December 2010 (02.12.2010) entire document	9-12
A	US 2004/0227093 A1 (KLASSEN et al) 18 November 2004 (18.11.2004) entire document	1-22
A	US 2011/0051901 A1 (MICHEL et al) 03 March 2011 (03.03.2011) entire document	1-22
A	US 2013/0083898 A1 (TAJIMA et al) 04 April 2013 (04.04.2013) entire document	1-22

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

10 November 2016

Date of mailing of the international search report

12 DEC 2016

Name and mailing address of the ISA/US

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