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(54) **DIRECT CONVERSION ENERGY
DISCRIMINATING CT DETECTOR WITH
OVER-RANGING CORRECTION**

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G01T 1/161 (2006.01)

(52) **U.S. Cl.** **378/19; 378/207; 250/363.09**

(58) **Field of Classification Search** 378/19, 378/98.8, 98.7, 116, 207; 250/370.09, 363.05, 250/252.1, 363.07, 363.09

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,218,624 A * 6/1993 LeMay 378/4

5,225,980 A *	7/1993	Hsieh et al.	378/18
5,228,069 A *	7/1993	Arenson et al.	378/19
5,262,871 A *	11/1993	Wilder et al.	348/307
5,376,795 A *	12/1994	Hasegawa et al.	250/363.04
5,400,378 A	3/1995	Toth	
5,548,123 A *	8/1996	Perez-Mendez et al.	250/370.09
5,789,737 A *	8/1998	Street	250/208.1
6,198,790 B1 *	3/2001	Pflaum	378/4
6,453,008 B1 *	9/2002	Sakaguchi et al.	250/370.09
2002/0085664 A1 *	7/2002	Bromberg et al.	378/19
2002/0097320 A1	7/2002	Zalis	
2003/0023163 A1	1/2003	Johnson et al.	
2003/0113267 A1	6/2003	Knopp et al.	
2003/0169847 A1 *	9/2003	Karellas et al.	378/98.3
2004/0136491 A1	7/2004	Iatrou et al.	
2004/0202283 A1 *	10/2004	Okumura et al.	378/145
2004/0264627 A1 *	12/2004	Besson	378/5

OTHER PUBLICATIONS

F. Rashid-Farrokhi et al., Local Tomography in Fan-Beam Geometry Using Wavelets, IEEE, 1996, 0-7803-3258-X/96, pp. 709-712.

* cited by examiner

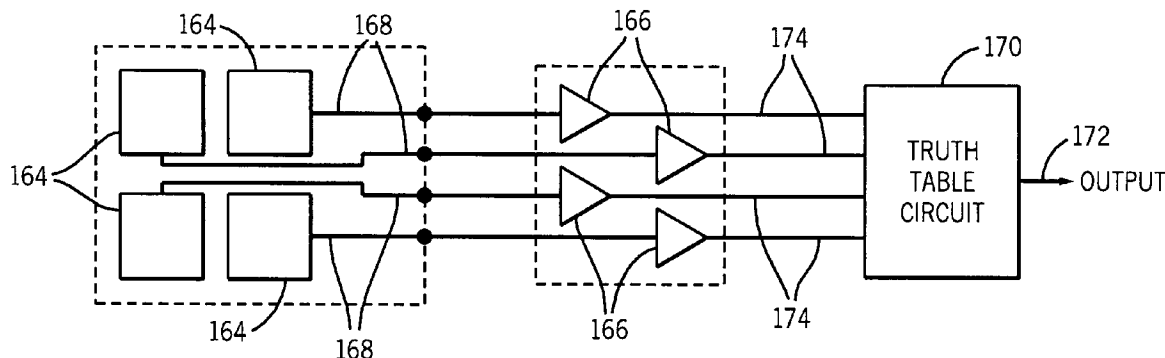
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(57) **ABSTRACT**

A CT detector capable of energy discrimination and direct conversion is disclosed. The detector includes multiple layers of semiconductor material with the layers having varying thicknesses. The detector is constructed to be segmented in the x-ray penetration direction so as to optimize count rate performance as well as avoid saturation. The detector also includes variable pixel pitch and a flexible binning of pixels to further enhance count rate performance.

12 Claims, 12 Drawing Sheets



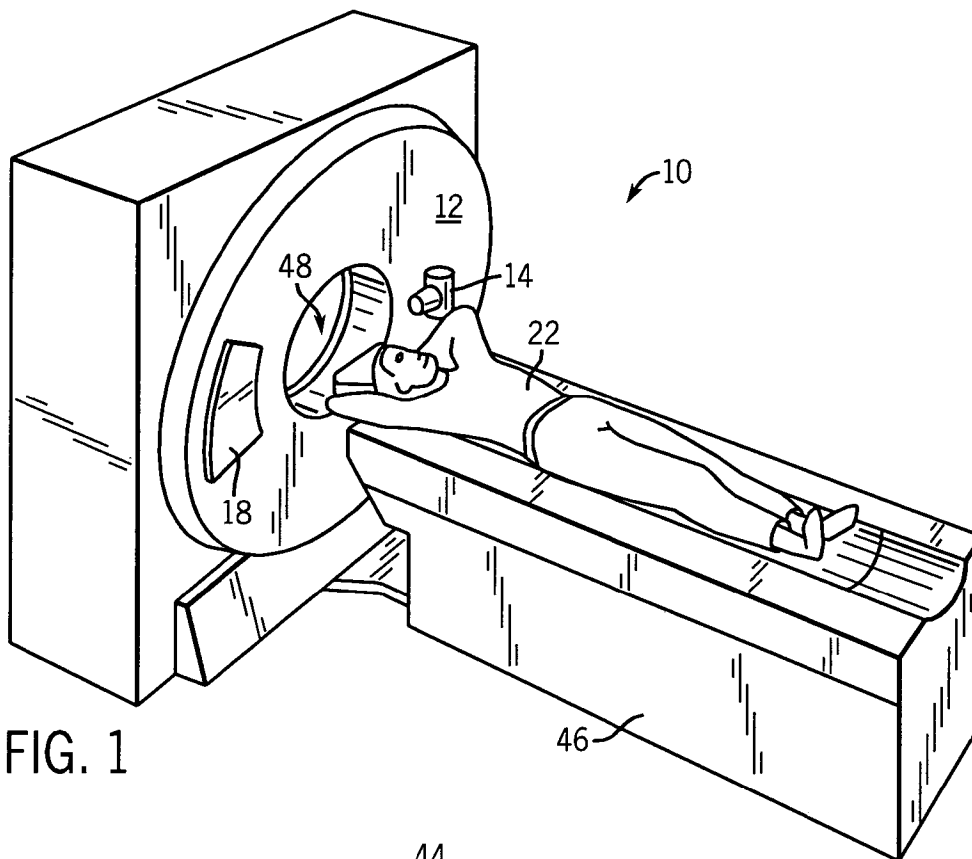


FIG. 1

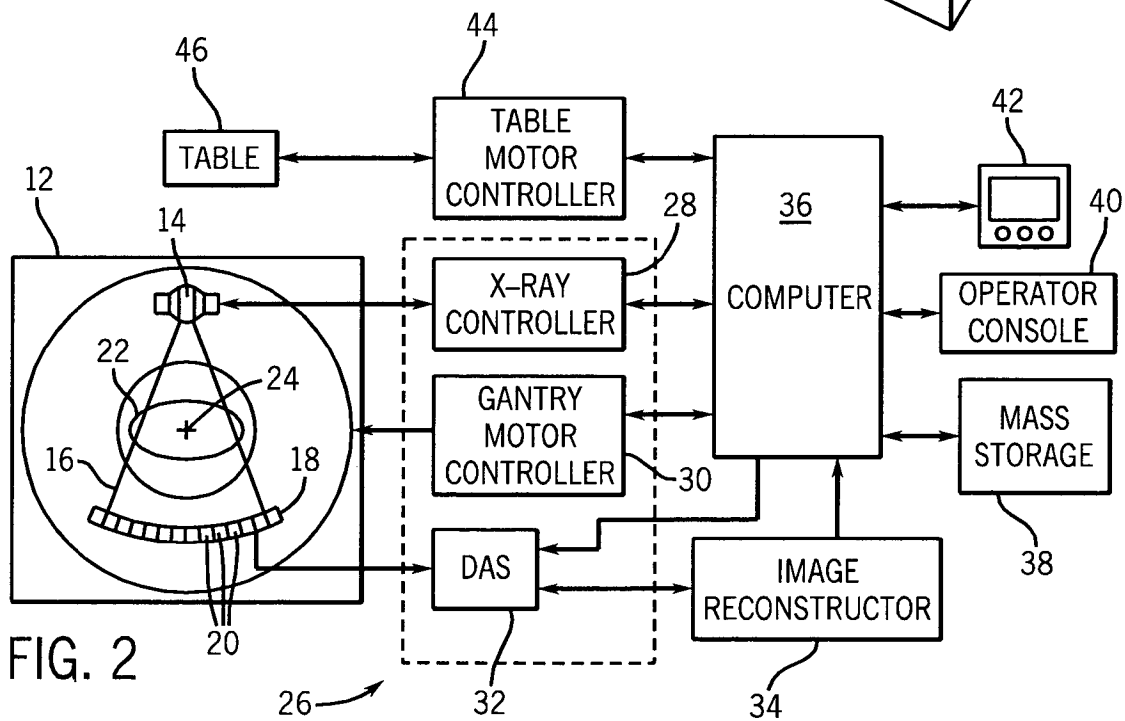


FIG. 2

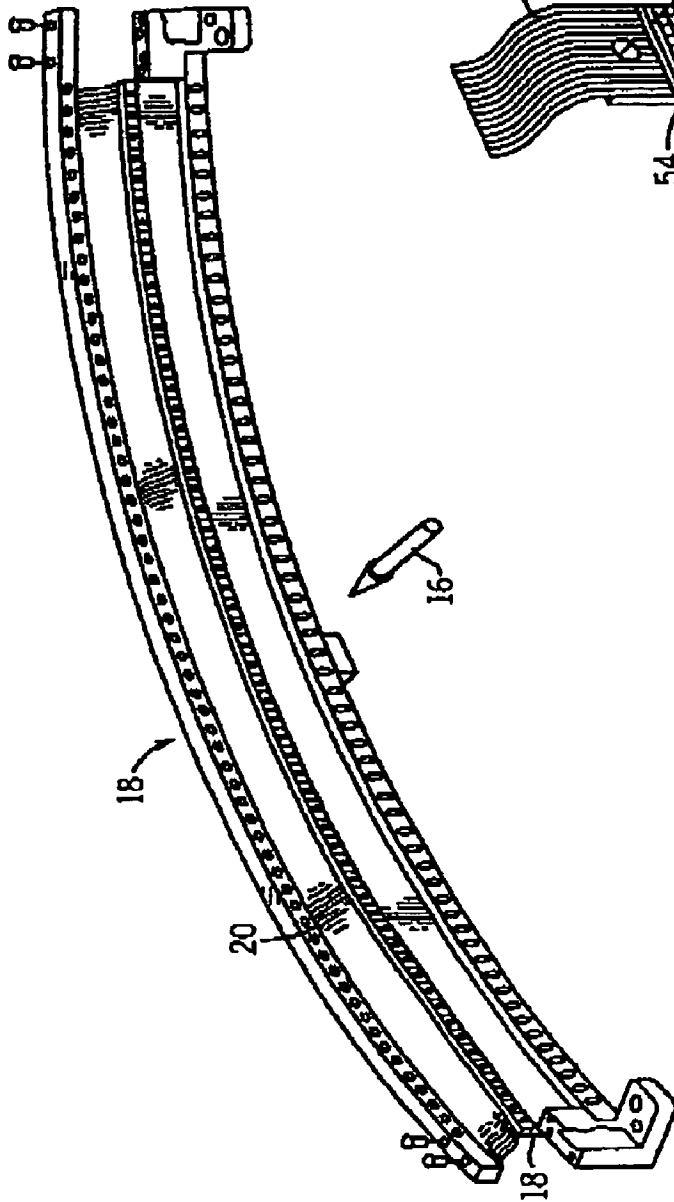


FIG. 3

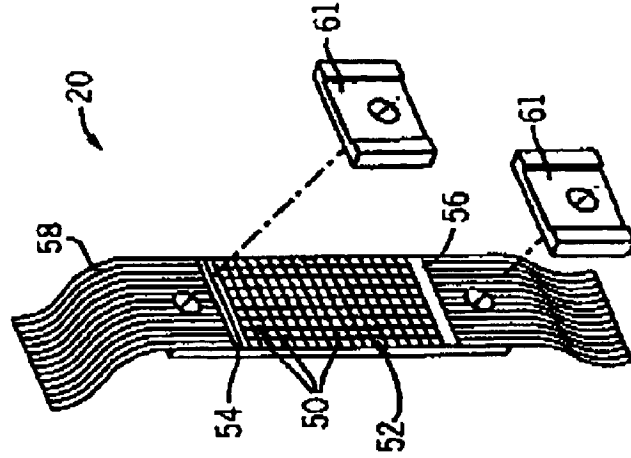


FIG. 4

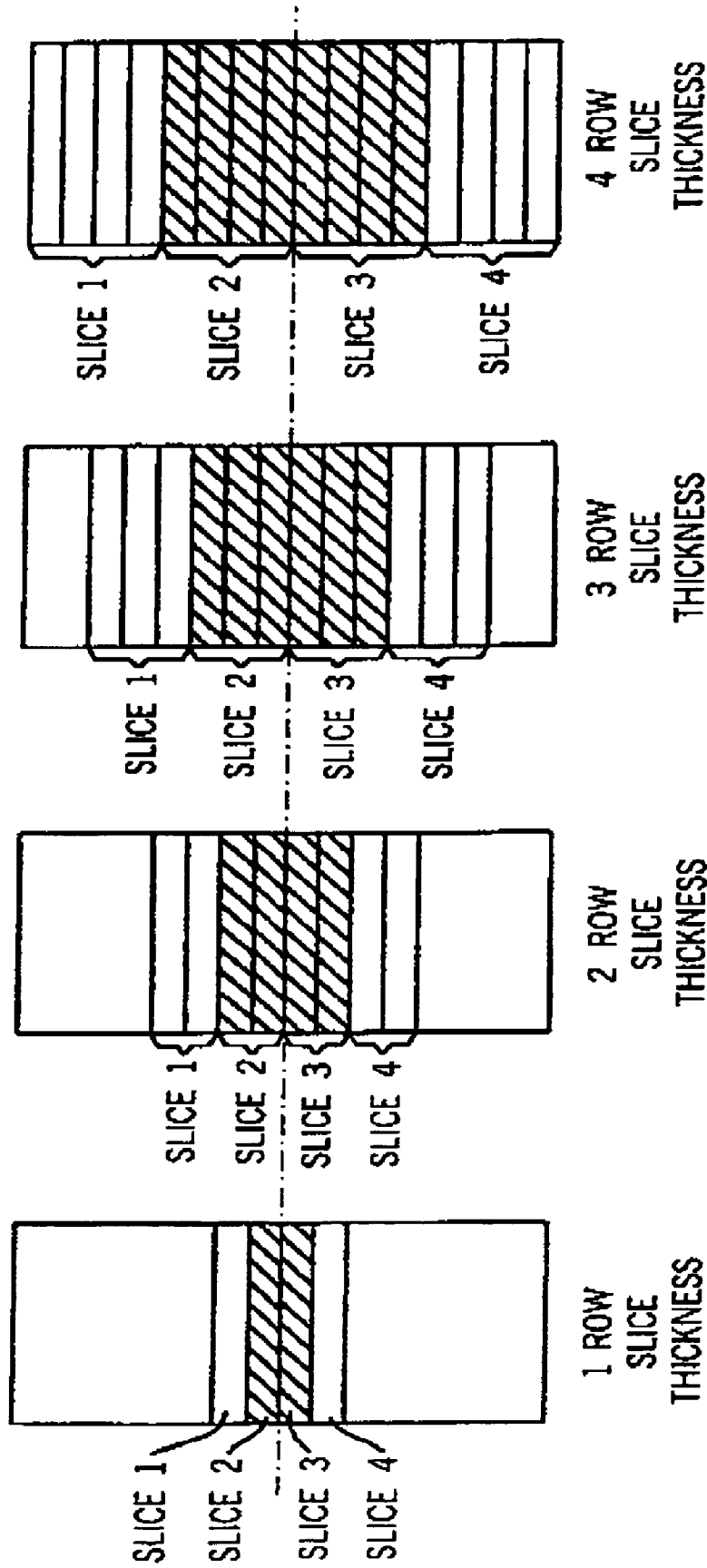
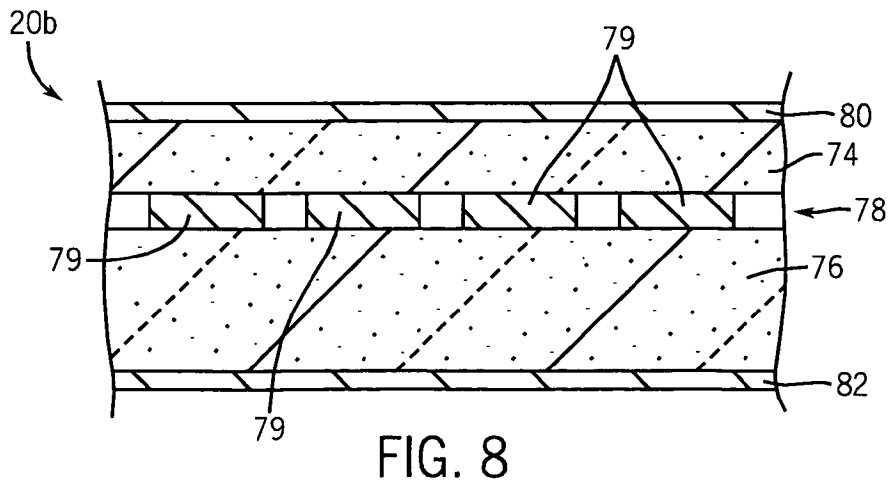
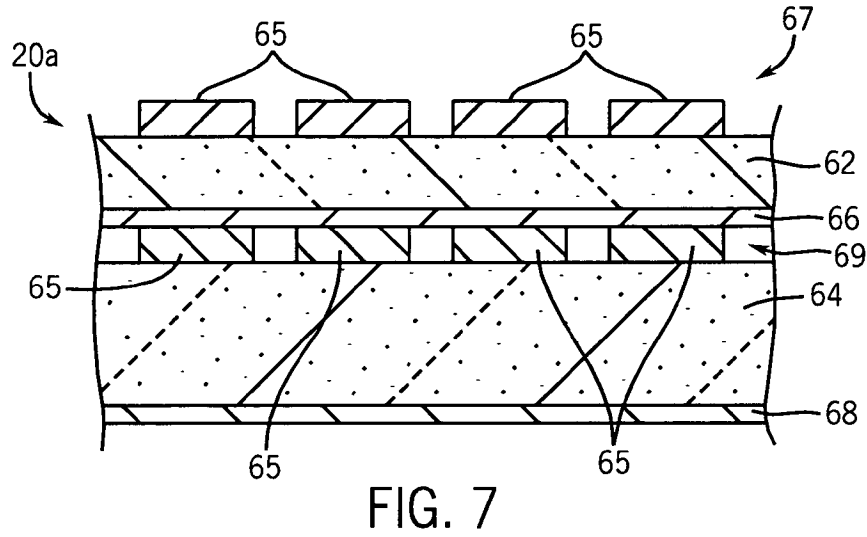
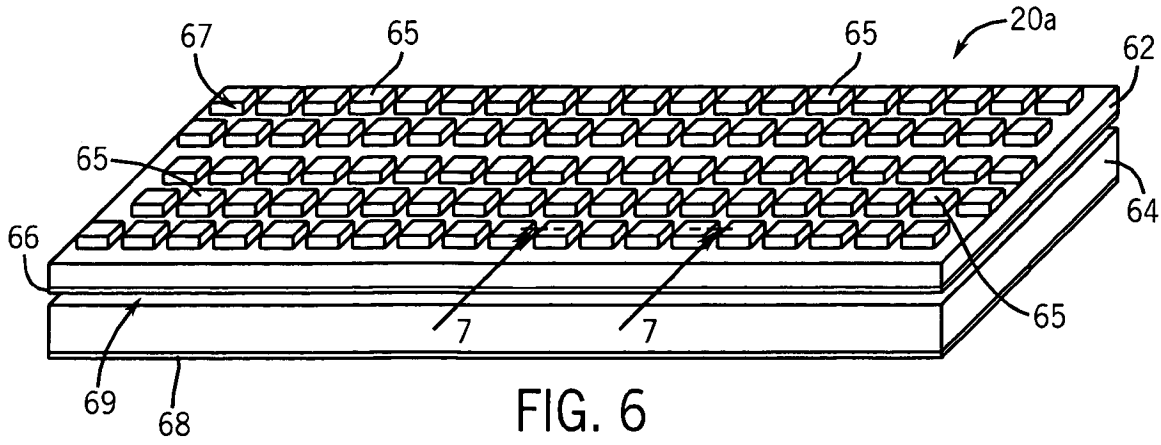
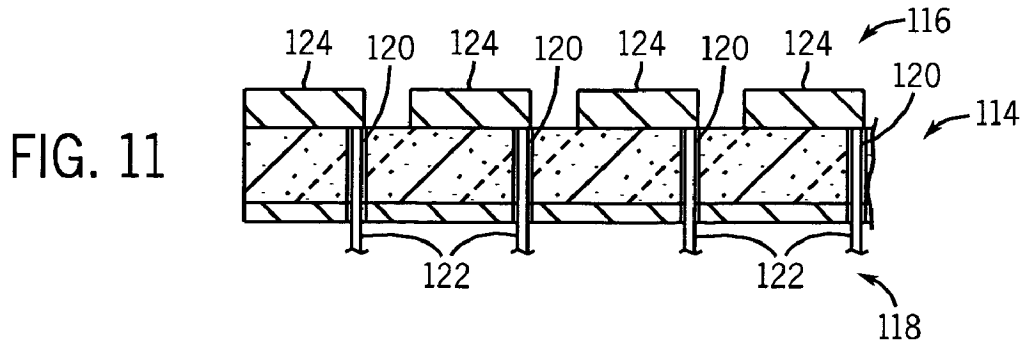
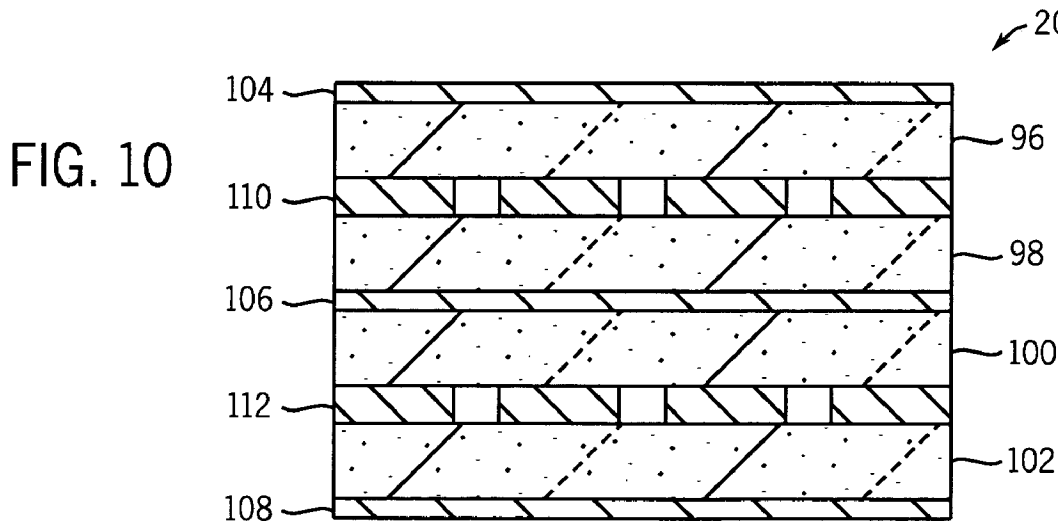
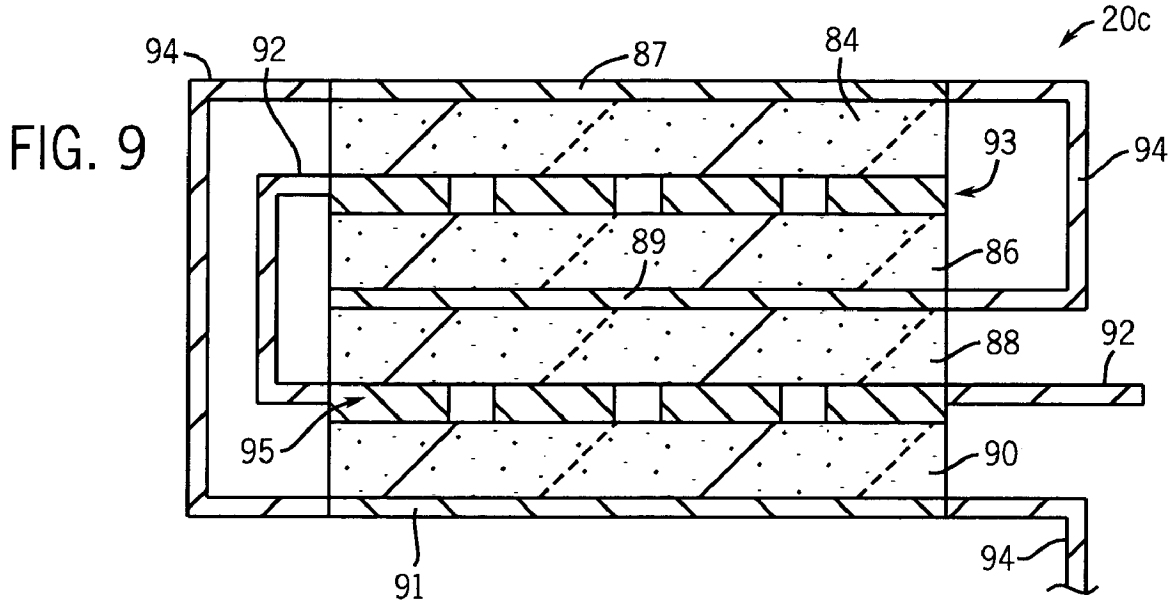


FIG. 5





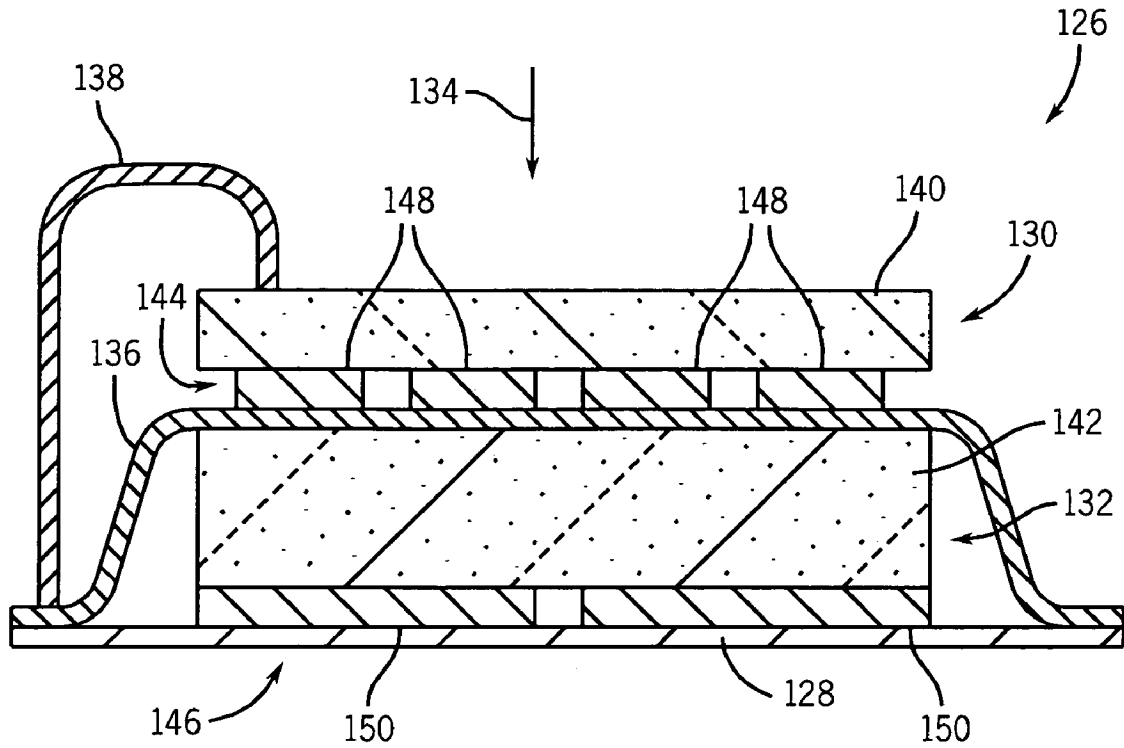


FIG. 12

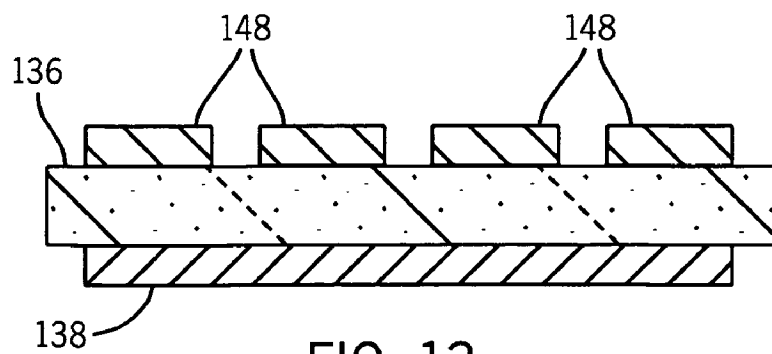
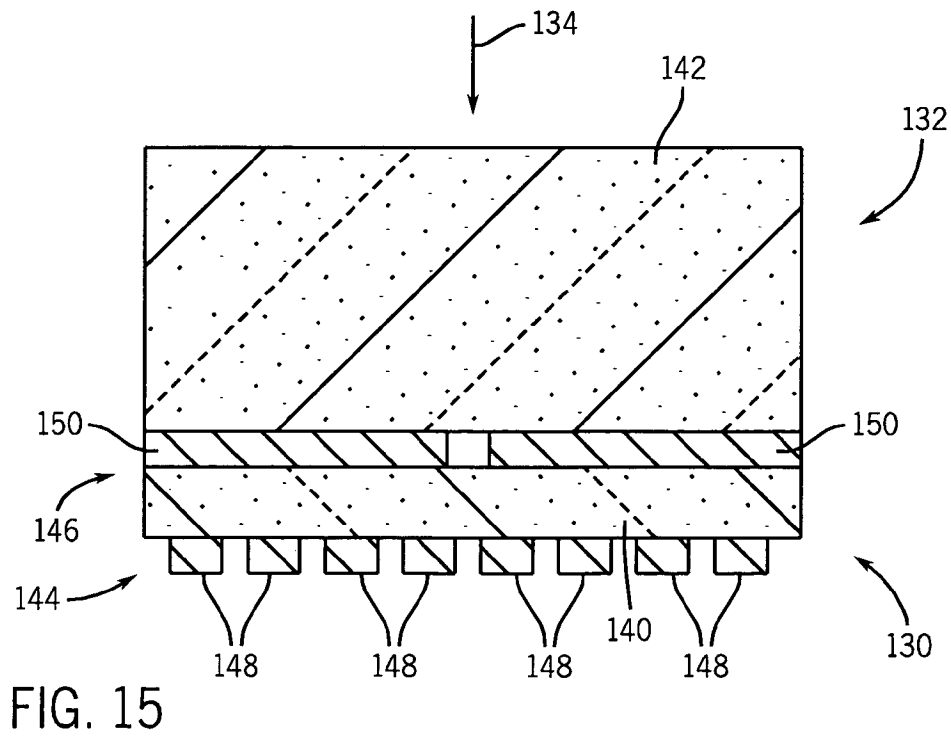
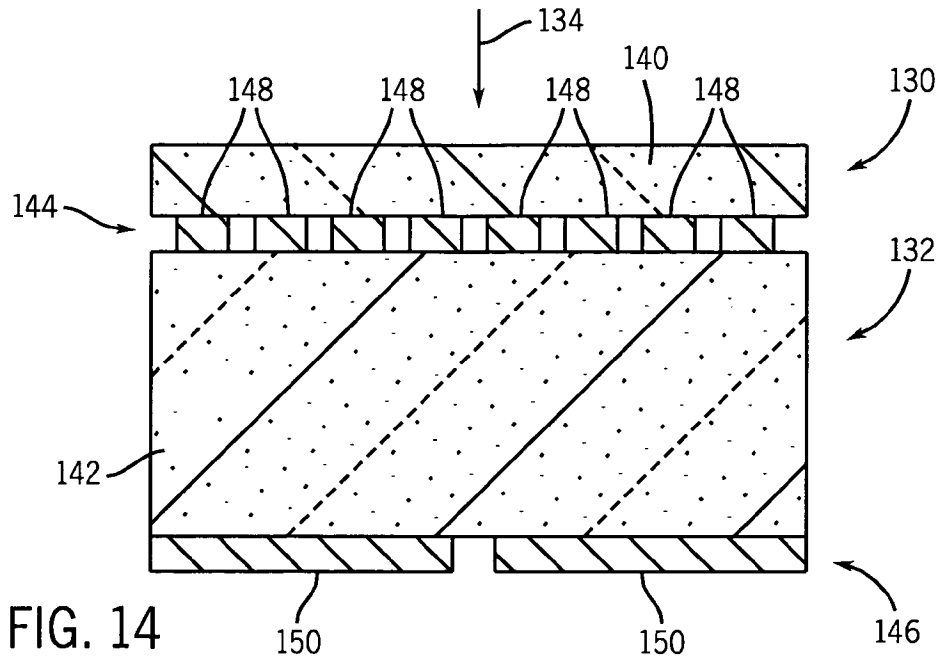


FIG. 13



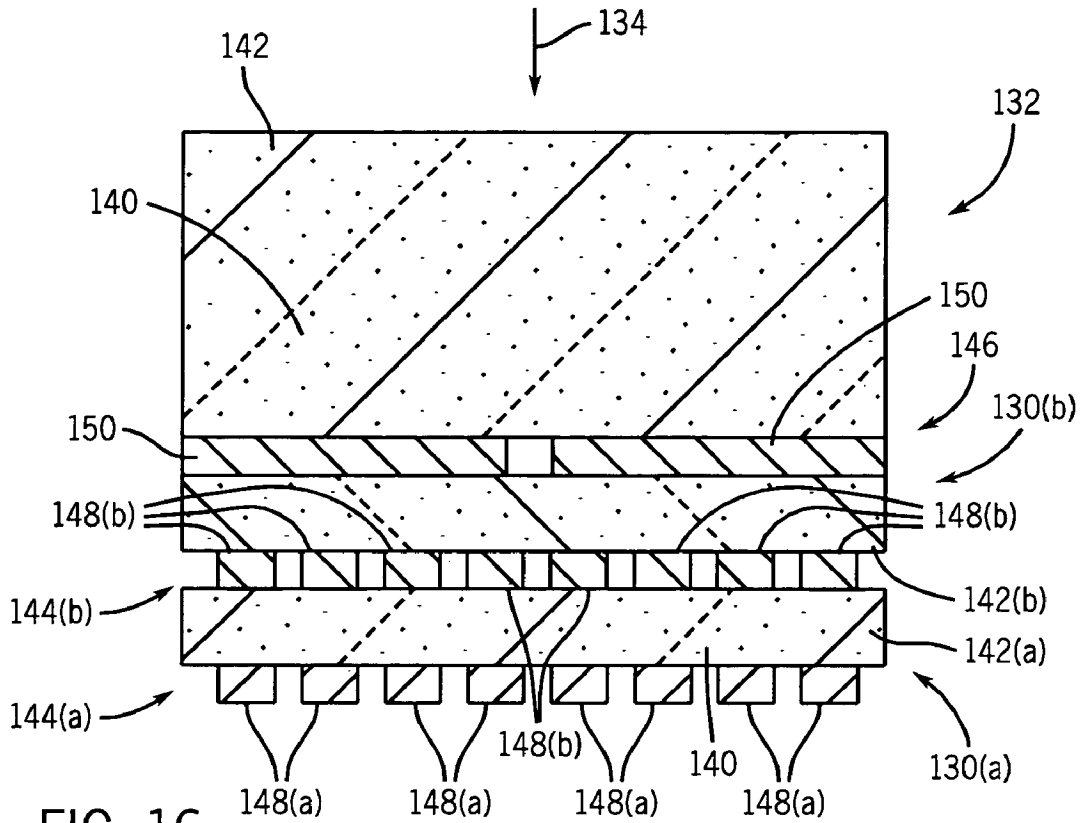


FIG. 16

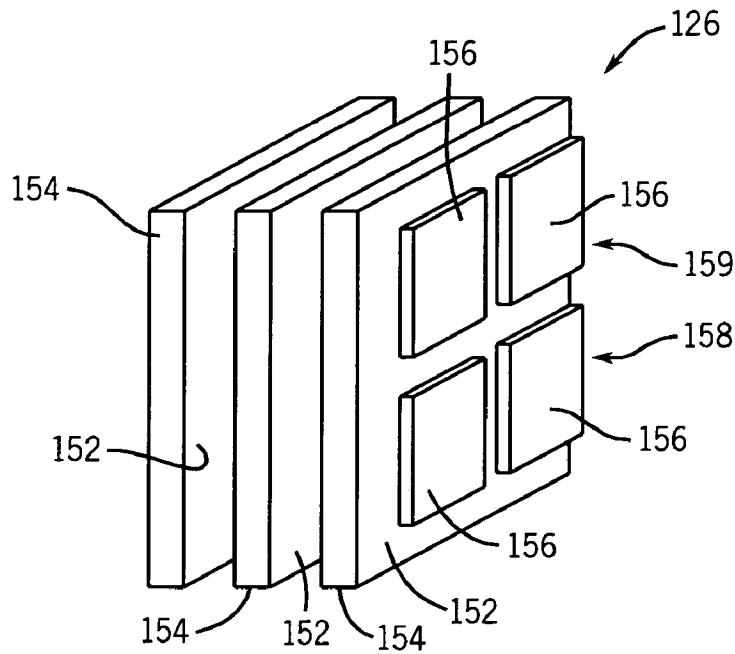


FIG. 17

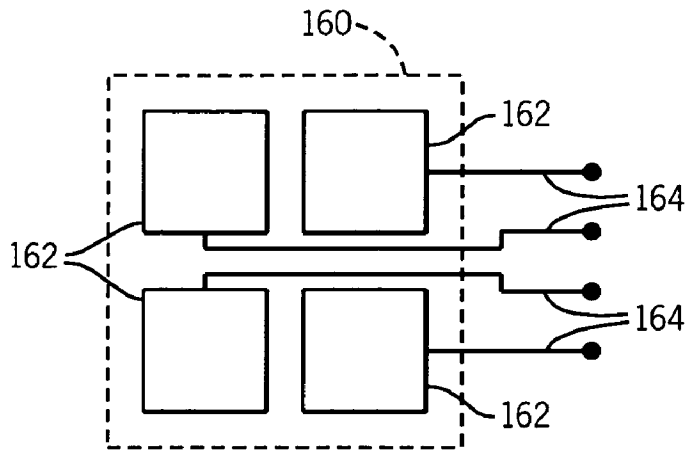


FIG. 18

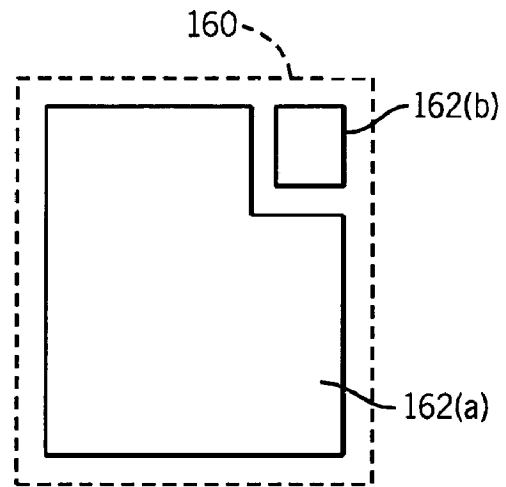


FIG. 19

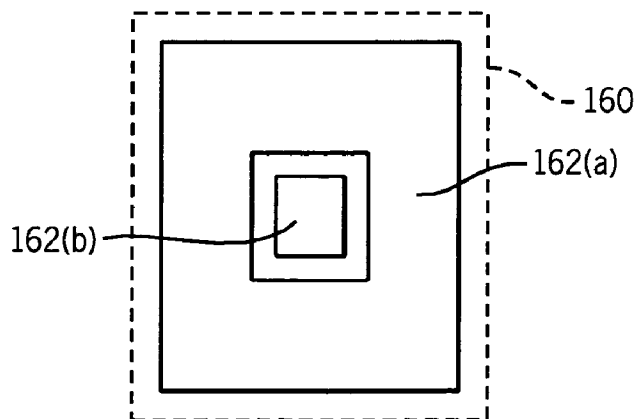


FIG. 20

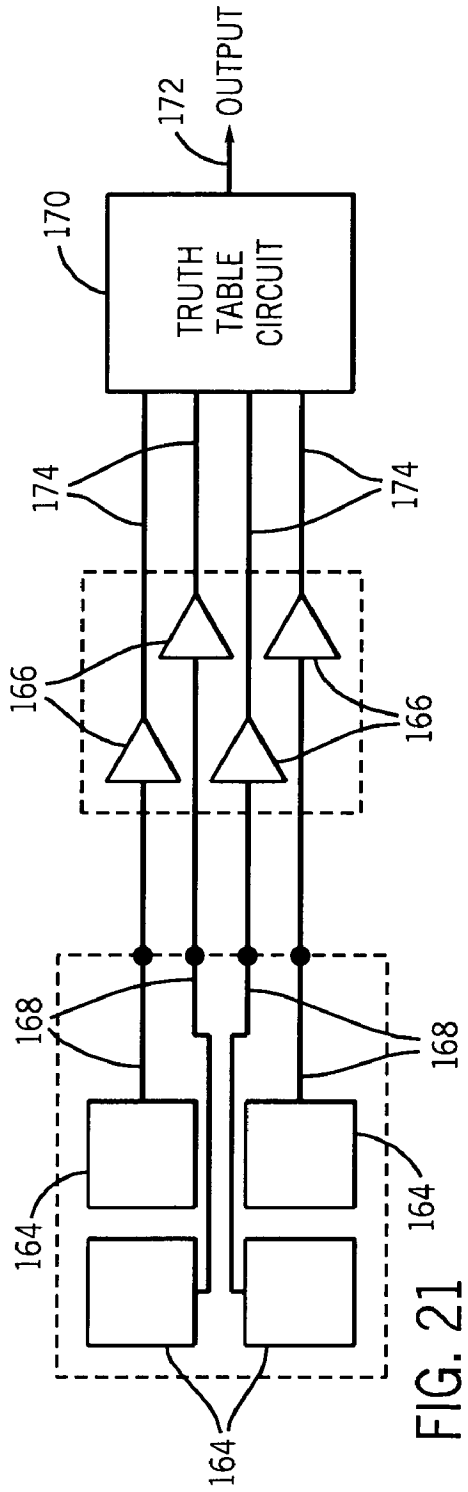


FIG. 21

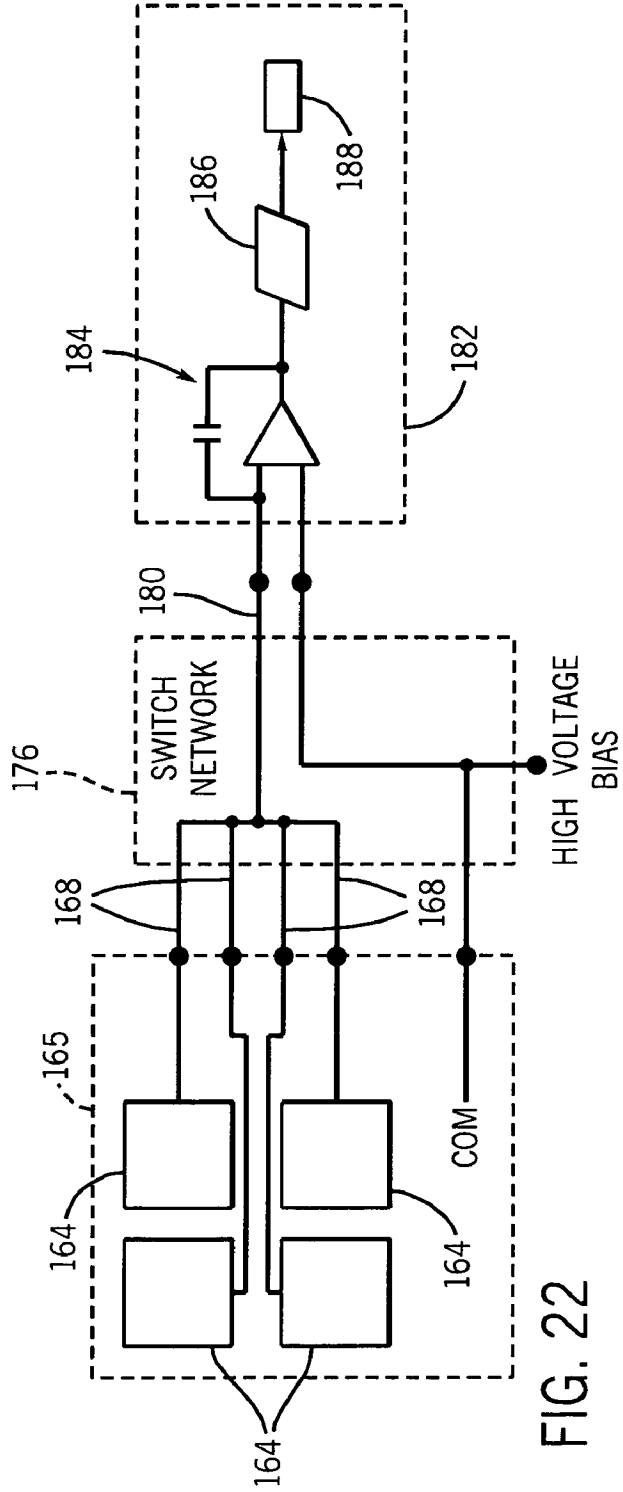


FIG. 22

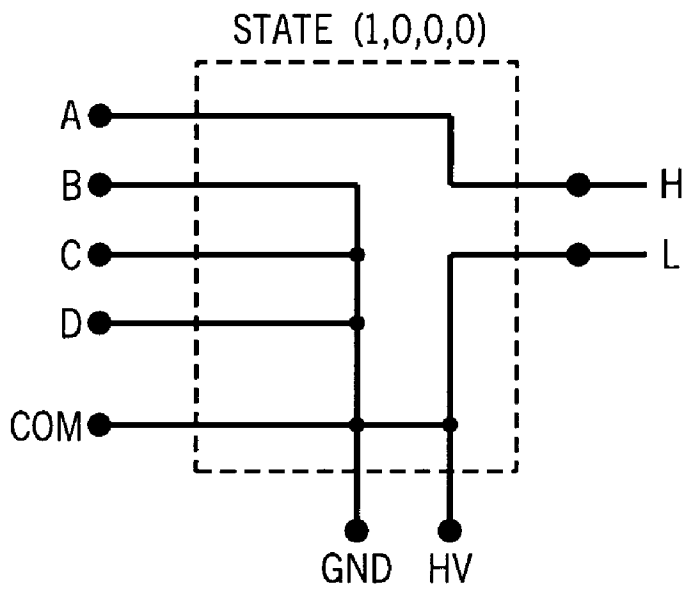


FIG. 23

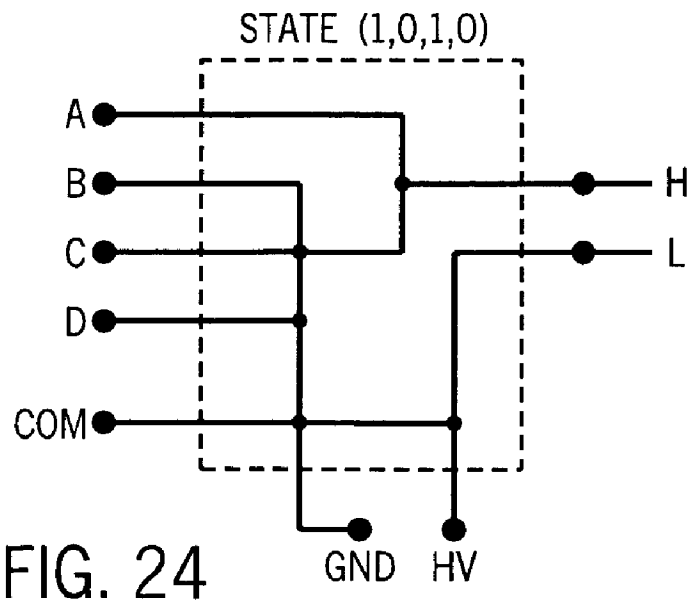


FIG. 24

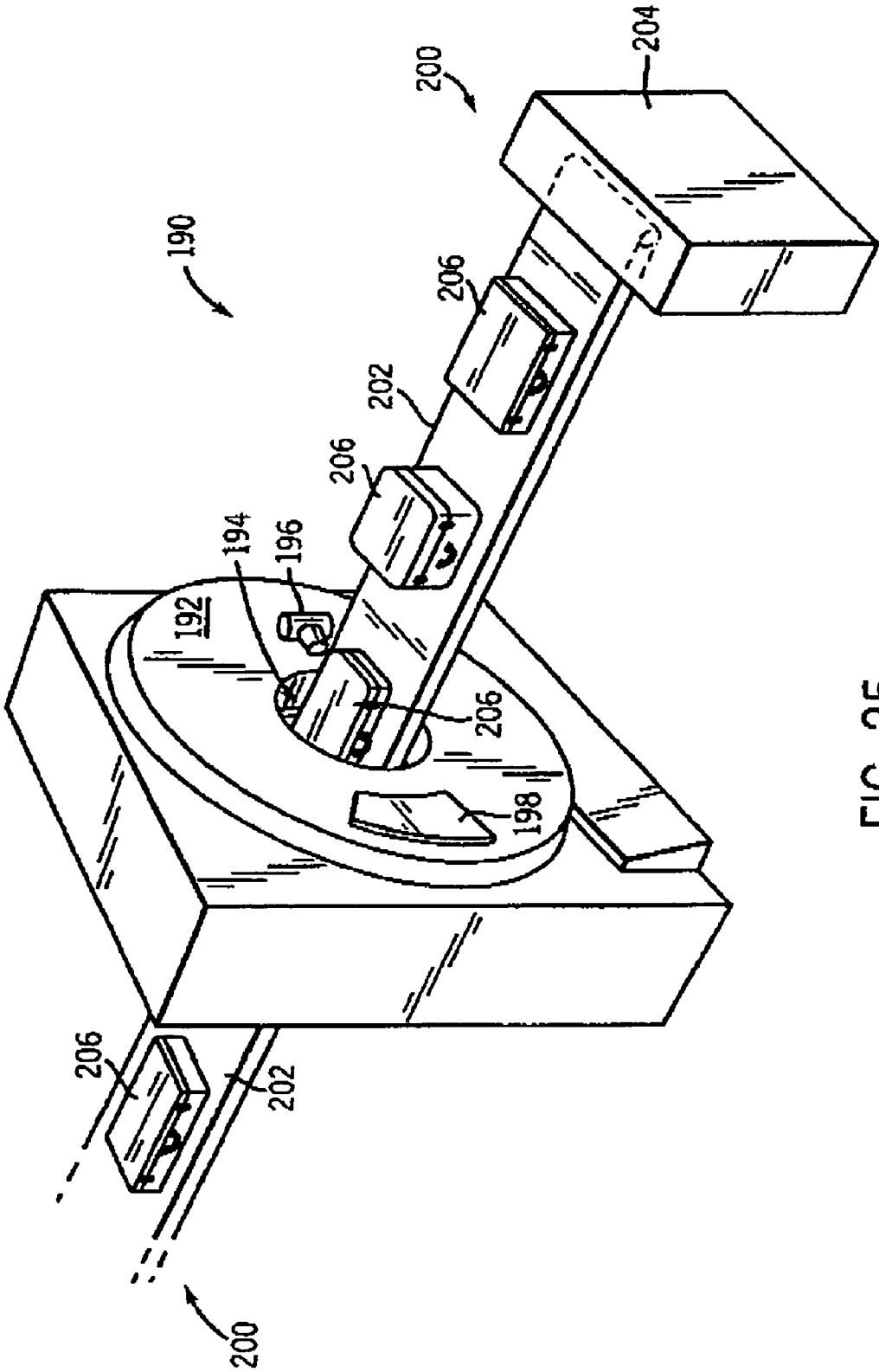


FIG. 25

**DIRECT CONVERSION ENERGY
DISCRIMINATING CT DETECTOR WITH
OVER-RANGING CORRECTION**

BACKGROUND OF THE INVENTION

The present invention relates generally to radiographic detectors for diagnostic imaging and, more particularly, to a multi-layer direct conversion CT detector capable of providing photon count and/or energy data with improved saturation characteristics and over-ranging self-correctability.

Typically, in radiographic imaging systems, such as x-ray and computed tomography (CT), an x-ray source emits x-rays toward a subject or object, such as a patient or a piece of luggage. Hereinafter, the terms "subject" and "object" may be interchangeably used to describe anything capable of being imaged. The beam, after being attenuated by the subject, impinges upon an array of radiation detectors. The intensity of the attenuated beam radiation received at the detector array is typically dependent upon the attenuation of the x-rays. Each detector element of the detector array produces a separate electrical signal indicative of the attenuated beam received by each detector element. The electrical signals are transmitted to a data processing system for analysis which ultimately produces an image.

In other typical radiographic imaging systems, positron emission tomography (PET) or single photon emission computed tomography (SPECT) a radiation source within the imaged object emits x-rays which are intercepted by a photon counting, energy sensitive x-ray detector. A CT system can be paired with a PET or SPECT system to produce a fused system (CT/SPECT or CT/PET) providing images indicating both anatomical structure and physiologically significant (i.e. functional) information. Such combined systems include a source that emits x-rays toward a x-ray detector and separate SPECT or PET detector which measures x-rays emitted from radiation source within the object.

In some CT imaging systems, for example, the x-ray source and the detector array are rotated within a gantry and within an imaging plane around the subject. X-ray sources for such CT imaging systems typically include x-ray tubes, which emit the x-rays as a fan beam emanating from a focal point. X-ray detectors for such CT imaging systems typically are configured in an circular arc centered to the focal spot. In addition, such detectors include a collimator for collimating x-ray beams received at the detector with focus to the focal spot. In addition, such detectors include a scintillator for converting x-rays to light energy adjacent the collimator, and a photodiode for receiving the light energy from an adjacent scintillator and producing electrical signals therefrom. Typically, each scintillator of a scintillator array converts x-rays to light energy. Each photodiode detects the light energy and generates a corresponding electrical signal as a function of the light emitted by a corresponding photodiode. The outputs of the photodiodes are then transmitted to the data processing system for image reconstruction.

In some SPECT and PET systems, for example, the one or more flat detector arrays is rotated within a gantry and within an imaging plane and around the subject. X-ray radiation sources within the imaged object emit photons in random directions. A x-ray detector typically includes a collimator for collimating x-ray beams received at the detector with focus for parallel rays contained within the imaging plane and perpendicular to the detector plane. In

addition, such detectors include a scintillator for converting x-rays to light energy adjacent the collimator, and a photomultiplier tube for receiving the light energy from an adjacent scintillator and producing electrical signals therefrom which are then transmitted to the data processing system for image reconstruction.

Conventional CT imaging systems utilize detectors that convert radiographic energy into current signals that are integrated over a time period, then measured and ultimately digitized. A drawback of such detectors however is their inability to provide data or feedback as to the number and/or energy of photons detected. That is, conventional CT detectors have a scintillator component and photodiode component wherein the scintillator component illuminates upon reception of radiographic energy and the photodiode detects illumination of the scintillator component and provides an electrical signal as a function of the intensity of illumination. While it is generally recognized that CT imaging would not be a viable diagnostic imaging tool without the advancements achieved with conventional CT detector design, a drawback of these detectors is their inability to provide energy discriminatory data or otherwise count the number and/or measure the energy of photons actually received by a given detector element or pixel. That is, the light emitted by the scintillator is a function of the number of x-rays impinged as well as the energy level of the x-rays. Under the charge integration operation mode, the photodiode is not capable of discriminating between the energy level or the photon count from the scintillation. For example, two scintillators may illuminate with equivalent intensity and, as such, provide equivalent output to their respective photodiodes. Yet, the number of x-rays received by each scintillator may be different as well as the x-rays intensity, but yield an equivalent light output.

A typical PET or SPECT system uses a photon counting, energy discriminating detector constructed from a scintillator and photomultiplier tube. Such detectors have large detector elements and as such are not readily adapted to CT applications requiring high resolution imaging to capture anatomical detail in the imaged object. Accordingly, recent detector developments have included the design of an energy discriminating, direct conversion detector that can provide photon counting and/or energy discriminating feedback with high spatial resolution. In this regard, the detector can be caused to operate in an x-ray counting mode, an energy measurement mode of each x-ray event, or both.

These energy discriminating, direct conversion detectors are capable of not only x-ray counting, but also providing a measurement of the energy level of each x-ray detected. Consequently, such a detector could potentially be used for SPECT or PET imaging. While a number of materials may be used in the construction of a direct conversion energy discriminating detector, semiconductors have been shown to be one preferred material.

A drawback of direct conversion semiconductor detectors, however, is that these types of detectors cannot count at the x-ray photon flux rates typically encountered with conventional CT systems, e.g. at or above 1 million counts per sec per millimeter squared (1.0 Mcps). The very high x-ray photon flux rate, above 1.0 Mcps, causes pile-up and polarization which ultimately leads to detector saturation. That is, these detectors typically saturate at relatively low x-ray flux level thresholds. Above these thresholds, the detector response is not predictable or has degraded dose utilization. For SPECT and PET, imaging flux levels are below 1.0 Mcps and such saturation in a semiconductor detector for SPECT and PET is not a practical concern. However, for CT,

saturation can occur at detector locations wherein small subject thickness is interposed between the detector and the radiographic energy source or x-ray tube. It has been shown that these saturated regions correspond to paths of low subject thickness near or outside the width of the subject projected onto the detector fan-arc. In many instances, the subject is more or less circular or elliptical in the effect on attenuation of the x-ray flux and subsequent incident intensity to the detector. In this case, the saturated regions represent two disjointed regions at extremes of the fan-arc. In other less typical, but not rare instances, saturation occurs at other locations and in more than two disjointed regions of the detector. In the case of an elliptical subject, the saturation at the edges of the fan-arc is reduced by the imposition of a bowtie filter between the subject and the x-ray source. Typically, the filter is constructed to match the shape of the subject in such a way as to equalize total attenuation, filter and subject, across the fan-arc. The flux incident to the detector is then relatively uniform across the fan-arc and does not result in saturation. What can be problematic, however, is that the bowtie filter may not be optimal given that a subject population is significantly less than uniform and not exactly elliptical in shape. In such cases, it is possible for one or more disjointed regions of saturation to occur or conversely to over-filter the x-ray flux and create regions of very low flux. Low x-ray flux in the projection will ultimately contribute to noise in the reconstructed image of the subject.

Detector saturation causes loss of imaging information and results in artifacts in x-ray projection and CT images. In addition, hysteresis and other non-linear effects occur at flux levels near detector saturation as well as flux levels over detector saturation. Direct conversion detectors are susceptible to a phenomenon called "polarization" where charge trapping inside the material changes the internal electric field, alters the detector count and energy response in an unpredictable way, and results in hysteresis where response is altered by previous exposure history. In particular, photon counting, direct conversion detectors, saturate due to the intrinsic charge collection time (i.e. dead time) associated with each x-ray photon event. Saturation will occur due to pulse pile-up when x-ray photon absorption rate for each pixel is on the order of the inverse of this charge collection time. The charge collection time is approximately proportional to thickness of the direct conversion layer for a fixed electric field and anode contact size; therefore, an increase in saturation rate is possible if the direct conversion layer is thinner. However, a sufficient thickness is required to stop almost all the x-rays. Incomplete collection of x-rays results in reduced image quality, i.e. a noisy image, and poor utilization of dose to the imaged object.

An additional factor in the charge collection time is the voltage applied across the layer thickness. A larger electric field (voltage/thickness) results in inverse proportionally smaller charge collection times and proportionally larger saturate rates. However, there is a reliability issue to routing of high voltage signals. Higher reliability can be obtained for lower voltages across smaller thicknesses of direct conversion layer. However, again, a sufficient thickness of the layer is required to sufficiently stop a majority of the x-rays.

Other types of detectors in addition to direct conversion detectors also saturate. A common example is the scintillator-photodiode arrangement connected to an integrating preamplifier. Charge created from each photon is routed to the preamplifier. As x-ray flux increases, the current to the preamplifier or total charge built up over an integration time period will increase. The readout electronics have a limiting

current or charge capability before saturating the amplifier. Amplifier saturation is associated with non-linear response and the loss of signal charge. This again results in poor dose utilization and image artifacts.

Another detector construction is a scintillator over photodiode connected to photon counting readout electronics. Similar constructions utilize a scintillator over avalanche-photodiode or photo-multiplier tube. Saturation of the x-ray flux rate in these photon-counting cases is also related to a dead time for clearing the charge before arrival of the next x-ray photon.

For photon counting, direct conversion detectors, a practical solution to x-ray flux rate saturation in imaging systems using x-ray sources operating at or above 1.0 Mcps range is not known. For these systems, a total thickness of the x-ray absorbing layer must be greater than 1.0 mm. The higher the energy of the x-rays; the higher the required thickness to sufficiently stop a predominance of the x-ray flux. A typical target value is to stop 95% or greater of the incident x-rays. For Cadmium Zinc Telluride (CZT) or Cadmium Telluride (CdTe), two possible direct conversion materials used for x-ray spectroscopy, the required thickness for diagnostic radiology and CT imaging is 3.0-5.0 mm in order to stop most of the x-rays generated from a source at 100-200 kVp. For CZT and CdTe, the saturation limit of 10^7 x-rays/sec/mm² is generally found for pixel size on the order of 1.0 mm and thicknesses of order 3.0-5.0 mm. This limit is directly related to the charge collection time for CZT. Higher flux rates are theoretically possible using of smaller pixels. Each pixel has a size-independent count rate limit set by the charge collection time. The saturation flux rate is set by the count rate limit divided by the area of the pixel. Therefore, the saturation flux rate increases as the pixel size decreases. Smaller pixels are also desirable because they make available higher spatial resolution information which can result in high resolution images. However, small pixel size results in higher cost and there are more channels per unit area which need to be connected to readout electronics.

In addition, smaller pixels or detector elements have larger perimeter to area ratios resulting in more cross-talk. The perimeter is a region where charge is shared between two or more pixels (i.e. cross-talk). This sharing of charge results in incomplete energy information and/or a miscount of x-ray photons because the readout electronics are not configured to combine simultaneous signals in neighboring pixels. Very high flux rates are possible with thin, photon counting, direct conversion silicon layers with pixel size <0.1 mm, but there is not sufficient stopping power in these thin layers to stop the x-rays. For integrating detectors, the size of the detector pixel and design of the preamplifier are balanced to handle an x-ray flux rate expected during imaging. For CT, the flux rate capability of the detector with integrating electronics is generally of the order 10^9 photons/sec/mm². For x-ray projection imagers operating with charge storage, integrating detectors, the flux rate capability is only of the same order. For photon counting detectors using scintillators and one of photodiodes/APDs/photomultipliers, the dead time of the x-ray conversion layer is very fast and the dead time is usually related to the bandwidth of the electronic readout, which can also be relatively high. The problem with these detectors is varied. In the case of photodiode, the electronic gain is not sufficient to overcome the electronic noise. In the case of APDs, there is additional gain but with associated gain-instability noise, temperature sensitivity and reliability issues. In the case of photomultiplier tubes, these devices are too large and costly for high resolution detectors covering large areas.

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Detector saturation can affect image quality by constraining the number of photons used to reconstruct the image and introducing image artifacts. A minimum image quality, therefore a minimum flux rate, is required to make use of the images. In this regard, when setting the configuration of the system such that sufficient flux is received at one area of the detector, then it is likely that another area of the detector will receive higher flux, and possibly, high enough to saturate the detector in this area. Higher flux in these other areas is not necessary for the image quality; however, the loss of data due to detector saturation may need to be addressed through correction algorithms in order to reduce image artifacts. For CT imaging, the reconstruction is not tolerant to missing or corrupted data. For example, if the center of the detector is illuminated with a minimum flux for image quality purposes, and if the illuminated object is compact, then detector cells at and beyond the periphery of the object's shadow can be saturated due to thin object thickness in these projected directions. The reconstruction of the data set with these uncorrected saturated values will cause severe artifacts in the image.

A number of imaging techniques have been developed to address saturation of any part of the detector. These techniques include maintenance of low x-ray flux across the width of a detector array, for example, by using low tube current or current that is modulated per view. However, this solution leads to increased scanned time. That is, there is a penalty that the acquisition time for the image is increased in proportion to the nominal flux needed to acquire a certain number of x-rays that meet image quality requirements.

With respect to combined CT and SPECT or CT and PET imaging, the availability of an energy discriminating detector with high flux rate capability provides the opportunity for a shared detector. The x-ray photon energies of SPECT are similar to those in CT, such that a semiconductor layer thickness can be designed to meet the requirements of both CT and SPECT. However, for PET, the photon energies are at 511 eV, about 5 times higher than that used for CT and SPECT.

It would therefore be desirable to design a direct conversion, energy discriminating CT detector that does not saturate at the x-ray photon flux rates typically found in conventional CT systems. It would be further desirable to design an x-ray management system that accommodates variations in x-ray flux across a CT detector assembly and compensates for over-ranging or saturating detectors. Such a detector and flux management system would allow the use of the same detector for both CT and SPECT imaging.

BRIEF DESCRIPTION OF THE INVENTION

The present invention is directed to a multilayer CT detector that performs at very high count rates that overcomes the aforementioned drawbacks.

A CT detector capable of energy discrimination and direct conversion is disclosed. Also, a dual-modality detector capable of both CT and single photon emission computed tomography (SPECT) detection is disclosed. The detector includes multiple layers of semiconductor material of varying thicknesses throughout the detector. In this regard, the detector is constructed to be segmented in the x-ray penetration direction to optimize count rate performance as well as avoid saturation. Further, the CT detector is constructed such that data corresponding to saturated regions can be estimated or otherwise determined from unsaturated regions. Additionally, the CT detector may be fabricated so as to have multiple detector elements or sub-pixels per contact area. In

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this regard, a dynamic and flexible combining of the outputs of the individual detector elements can be carried out to inhibit use of data from a saturated detector element.

The CT detector supports not only x-ray photon counting, but energy measurement or tagging as well. As a result, the present invention supports the acquisition of both anatomical detail as well as tissue characterization information. In this regard, the energy discriminatory information or data may be used to reduce the effects of beam hardening and the like. Further, these detectors support the acquisition of tissue discriminatory data and therefore provide diagnostic information that is indicative of disease or other pathologies. For example, detection of calcium in a plaque in a view is possible. This detector can also be used to detect, measure, and characterize materials that may be injected into a subject such as contrast agents and other specialized materials such as targeting agents. Contrast materials can, for example, include iodine that is injected into the blood stream for better visualization.

Therefore, in accordance with one aspect of the present invention, a CT detector is disclosed and includes a first direct conversion layer having a first array of electrical contacts and constructed to directly convert radiographic energy to electrical signals representative of energy sensitive radiographic data. The first direct conversion layer is also designed to saturate at a first saturation threshold. The CT detector further includes a second direct conversion layer having a second array of electrical contacts and constructed to directly convert radiographic energy to electrical signals representative of energy sensitive radiographic data. The second direct conversion layer is designed to saturate at a second saturation threshold different from the first saturation threshold.

In accordance with another aspect, the present invention includes a radiographic imaging system having a radiation source to project radiographic energy toward a subject to be scanned and a detector assembly to receive radiographic energy from the radiation source and attenuated by the subject. The detector assembly includes an array of detectors whereby each detector is designed to provide photon count and/or energy discriminatory output. The imaging system also includes a computer programmed to detect pile-up and over-ranging in a section of a given detector and determine appropriate output for the over-ranging section of the given detector from non-over-ranging sections of the given detector.

According to another aspect, the present invention includes a CT scanner having a rotatable gantry with an opening to receive a subject to be scanned. The CT scanner also includes an x-ray source configured to project x-rays toward the subject as well as a detector array having a plurality of detectors designed to provide energy sensitive output in response to detected x-rays. A data acquisition system (DAS) is connected to the detector array and configured to receive the detector outputs. The CT scanner also includes an image reconstructor connected to the DAS and configured to reconstruct an image of the subject from the detector outputs received by the DAS. The CT scanner further includes means for determining an output for a given detector of the detector array when a portion of the detector has reached an x-ray saturation state.

Various other features and advantages of the present invention will be made apparent from the following detailed description and the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The drawings illustrate one preferred embodiment presently contemplated for carrying out the invention.

In the drawings:

FIG. 1 is a pictorial view of a CT imaging system.

FIG. 2 is a block schematic diagram of the system illustrated in FIG. 1.

FIG. 3 is a perspective view of one embodiment of a CT system detector assembly.

FIG. 4 is a perspective view of a CT detector incorporating the present invention.

FIG. 5 is illustrative of various configurations of the detector in FIG. 4 in a four-slice mode.

FIG. 6 is a partial perspective view of a two-layer detector in accordance with the present invention.

FIG. 7 is a cross-sectional view of FIG. 6 taken along lines 7-7 thereof.

FIGS. 8-10 illustrate cross-sectional views of direct conversion detectors in accordance with several additional embodiments of the present invention.

FIG. 11 is a cross-sectional view illustrating signal feedthroughs that are created in another embodiment of the invention.

FIG. 12 is a cross-sectional schematic view of a CT detector in accordance with another embodiment of the present invention.

FIG. 13 is a cross-sectional view of an alternate embodiment of a portion of a CT detector according to the present invention.

FIG. 14 is a cross-sectional view of a portion of a CT detector in accordance with yet another embodiment of the present invention.

FIG. 15 is a cross-sectional view of yet another embodiment of a CT detector according to the present invention.

FIG. 16 is a cross-sectional schematic view similar to FIGS. 13-15 illustrating an alternate embodiment of the present invention.

FIG. 17 is a perspective view of a portion of a CT detector with its components oriented in a vertical arrangement.

FIG. 18 is a top view schematic illustrating sub-pixelization of a detector element area according to the present invention.

FIG. 19 is a top view of a single CT detector element area illustrating asymmetrical sub-pixelization thereof in accordance with another embodiment of the present invention.

FIG. 20 is a top view of an alternate asymmetrical sub-pixelization for a single CT detector element area in accordance with an alternate embodiment of the present invention.

FIG. 21 is a block schematic illustrating combining the output of each sub-pixel of a given CT detector element area in accordance with another embodiment of the present invention.

FIG. 22 is a circuit schematic illustrating a flexible binning of sub-pixel outputs of a given CT detector element area in accordance with another embodiment of the present invention.

FIGS. 23-24 are circuit schematics illustrating binning of sub-pixel outputs of a given CT detector element area based on the saturation state of each sub-pixel according to a further embodiment of the invention.

FIG. 25 is a pictorial view of a CT system for use with a non-invasive package inspection system.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

The operating environment of the present invention is described with respect to a four-slice computed tomography (CT) system. However, it will be appreciated by those skilled in the art that the present invention is equally applicable for use with single-slice or other multi-slice configurations. Moreover, the present invention will be described with respect to the detection and conversion of x-rays. However, one skilled in the art will further appreciate that the present invention is equally applicable for the detection and conversion of other radiographic energy.

Referring to FIGS. 1 and 2, a computed tomography (CT) imaging system 10 is shown as including a gantry 12 representative of a "third generation" CT scanner. Gantry 12 has an x-ray source 14 that projects a beam of x-rays 16 toward a detector assembly 18 on the opposite side of the gantry 12. Detector assembly 18 is formed by a plurality of detectors 20 which together sense the projected x-rays that pass through a medical patient 22. Each detector 20 produces an electrical signal that represents not only the intensity of an impinging x-ray beam but is also capable of providing photon or x-ray count data, and hence the attenuated beam as it passes through the patient 22. During a scan to acquire x-ray projection data, gantry 12 and the components mounted thereon rotate about a center of rotation 24.

Rotation of gantry 12 and the operation of x-ray source 14 are governed by a control mechanism 26 of CT system 10. Control mechanism 26 includes an x-ray controller 28 that provides power and timing signals to an x-ray source 14 and a gantry motor controller 30 that controls the rotational speed and position of gantry 12. A data acquisition system (DAS) 32 in control mechanism 26 reviews data from detectors 20 and converts the data to digital signals for subsequent processing. An image reconstructor 34 receives sampled and digitized x-ray data from DAS 32 and performs high speed reconstruction. The reconstructed image is applied as an input to a computer 36 which stores the image in a mass storage device 38.

Computer 36 also receives commands and scanning parameters from an operator via console 40 that has a keyboard. An associated cathode ray tube display 42 allows the operator to observe the reconstructed image and other data from computer 36. The operator supplied commands and parameters are used by computer 36 to provide control signals and information to DAS 32, x-ray controller 28 and gantry motor controller 30. In addition, computer 36 operates a table motor controller 44 which controls a motorized table 46 to position patient 22 and gantry 12. Particularly, table 46 moves portions of patient 22 through a gantry opening 48.

As shown in FIGS. 3 and 4, detector assembly 18 includes a plurality of detectors 20, with each detector including a number of detector elements 50 arranged in a cellular array. A collimator (not shown) is positioned to collimate x-rays 16 before such beams impinge upon the detector assembly 18. In one embodiment, shown in FIG. 3, detector assembly 18 includes 57 detectors 20, each detector 20 having an array size of 16x16. As a result, assembly 18 has 16 rows and 912 columns (16x57 detectors) which allows 16 simultaneous slices of data to be collected with each rotation of gantry 12.

Switch arrays 54 and 56, FIG. 4, are multi-dimensional semiconductor arrays coupled between cellular array 52 and DAS 32. Switch arrays 54 and 56 include a plurality of field effect transistors (FET) (not shown) arranged as multi-dimensional array and are designed to combine the outputs

of multiple cells to minimize the number of data acquisition channels and associated cost. The FET array includes a number of electrical leads connected to each of the respective detector elements **50** and a number of output leads electrically connected to DAS **32** via a flexible electrical interface **58**. Particularly, about one-half of detector element outputs are electrically connected to switch **54** with the other one-half of detector element outputs electrically connected to switch **56**. Each detector **20** is secured to a detector frame by mounting brackets **61**.

It is contemplated and recognized that for some applications, the count rate limitation of the FET arrays may make them less desirable. In this regard, as will be described, each detection pixel or cell is connected to a channel of electronics.

Switch arrays **54** and **56** further include a decoder (not shown) that enables, disables, or combines detector element outputs in accordance with a desired number of slices and slice resolutions for each slice. Decoder, in one embodiment, is a decoder chip or a FET controller as known in the art. Decoder includes a plurality of output and control lines coupled to switch arrays **54** and **56** and DAS **32**. In one embodiment defined as a 16 slice mode, decoder enables switch arrays **54** and **56** so that all rows of the detector assembly **18** are activated, resulting in 16 simultaneous slices of data for processing by DAS **32**. Of course, many other slice combinations are possible. For example, decoder may also select from other slice modes, including one, two, and four-slice modes.

As shown in FIG. **5**, by transmitting the appropriate decoder instructions, switch arrays **54** and **56** can be configured in the four-slice mode so that the data is collected from four slices of one or more rows of detector assembly **18**. Depending upon the specific configuration of switch arrays **54** and **56**, various combinations of detectors **20** can be enabled, disabled, or combined so that the slice thickness may consist of one, two, three, or four rows of detector elements **50**. Additional examples include, a single slice mode including one slice with slices ranging from 1.25 mm thick to 20.0 mm thick, and a two slice mode including two slices with slices ranging from 1.25 mm thick to 10.0 mm thick. Additional modes beyond those described are contemplated.

As described above, each detector **20** is designed to directly convert radiographic energy to electrical signals containing energy discriminatory or photon count data. The present invention contemplates a number of configurations for these detectors, its components, and the manner in which data is read out. Notwithstanding the distinctions between each of these embodiments, each detector does share two common features. One of these features is the multilayer arrangement of semiconductor films or layers. In a preferred embodiment, each semiconductor film is fabricated from Cadmium Zinc Telluride (CZT). However, one skilled in the art will readily recognize that other materials capable of the direct conversion of radiographic energy may be used. The other common feature between the various embodiments is the use of interstitial or intervening metallized films or layers separating the semi-conducting layers. As will be described, these metallized layers are used to apply a voltage across a semiconductor layer as well as collect electrical signals from a semiconductor layer. As will also be described, detectors with such a design have improved saturation characteristics and photon count fidelity.

It is generally well known that the charge collection time of a semiconductor layer is inversely related to the maximum periodic count rate saturation threshold (MPR) of the

layer. A thinner layer will have faster collection of charges and higher MPR. However, the thinner layer will stop a smaller fraction of the incident x-rays. The charge collection time is approximately proportional to a dimension d , which is the smaller of either the thickness of the detector or the pixel contact size, whereas the radiographic energy deposition efficiency is exponentially increasing with thickness. The count rate performance for a CZT detector may be defined by:

$$MPR = \frac{\mu_e E}{d}$$

From this definition, assuming an equal contact size and thickness of $d=0.3$ cm and an electric field E of 1000 V/cm, and with a μ_e of about 1000 $\text{cm}^2/(\text{V sec})$, a maximum periodic count rate of 3.0 megacounts/sec may be achieved. Since the arrival of x-rays is not periodic but random, significant saturation effects will occur at $10\times$ lower average rate. In other words, the count rate of a CZT semiconductor layer that is 3.0 mm thick may have a count rate performance in the range of 0.3-3.0 megacounts/sec. However, as will be described, constructing a direct conversion semiconductor detector with multiple layers with the cumulative thickness of a single thicker layer can improve count rate performance.

Moreover, thinner conversion layers not only improve count rate performance due to a reduction of charge collection time, but also provide an improvement in charge collection efficiency thereby reducing polarization, detector count and energy response fidelity. Thinner conversion layers also reduce charge sharing between pixel elements thereby improving energy discrimination performance and spatial resolution.

Improvement in flux rate performance through the segmenting of the detector into multiple thin layers can be attributed to a number of factors. First, having multiple layers divides the total flux rate among the different layers. Each layer will experience only a fraction of the total flux. For example, incomplete x-ray attenuation of the first layer, which is thin (relative to the attenuation depth of x-rays), will insure that saturation of this layer will be at a higher count rate than that of a thick layer that stops all the x-rays.

A second factor is that the thickness of the layers can be configured to insure that if one layer does saturate, another layer is non-saturated and gives valid data for that view. For example, if one of the layers is constructed such that it stops only 5% of the x-rays, then it will saturate at $20\times$ the flux rate a thick layer designed to stop all the x-rays. A third factor is that charge collection time decreases as layer thickness and pixel size decrease. The charge collection time is approximately proportional to either the thickness or pixel contact size, whichever is smaller, divided by the mobility and electric field across the layer. Smaller thicknesses and/or pixel size gives higher flux rate limit for that layer.

A fourth factor is that thinner layers also yield a reduction in cross-talk. The impact of pixel size on cross-talk is approximately given by the effective perimeter area over the total pixel area. That is, cross-talk is scaled by a factor $4W^*aT/W$ where W is the pixel pitch and aT is a charge spreading length proportional to the layer thickness. Therefore, cross-talk decreases as the layer thickness decreases. The competing effects of flux rate saturation and cross-talk can be traded off by study of their impact on the detective quantum efficiency, (DQE(f)) an important figure of merit for x-ray imaging detectors. DQE falls off as a function of

count rate, less so for thinner layers. The design methodology for optimization of the number of layers and their thickness is predicated upon obtaining the greatest count rate before which the DQE(f) has decreased below any point on a certain threshold curve.

A fifth factor is the reduction in polarization due to the more efficient collection of electrons and holes. In a thinner layer, the electrons and holes are able to travel a smaller distance before being collected; therefore, the electron and holes are less susceptible to trapping.

In addition to these five factors for improved count rate limit upon use of thin layers, the flux rate limit (i.e. count rate per unit area) is improved by using smaller pixel size which is favored in thin layers because of reduced crosstalk.

Referring now to FIG. 6, a portion of a two-layered CZT or direct conversion detector **20a** in accordance with one embodiment of the present invention is shown in perspective. Detector **20a** is defined by a first semiconductor layer **62** and a second semiconductor layer **64**. During the fabrication process, each semiconductor layer **62**, **64** is constructed to have a number of electronically pixilated structures or pixels to define a number of detection elements or contacts **65**. This electronic pixilation is accomplished by applying a 2D array **67**, **69** of electrical contacts **65** onto a layer **62**, **64** of direct conversion material. Moreover, in a preferred embodiment, this pixilation is defined two-dimensionally across the width and length of each semiconductor layer **62**, **64**.

Detector **20a** includes a contiguous high voltage electrode **66**, **68** for semiconductor layers **62**, **64**, respectively. Each high voltage electrode **66**, **68** is connected to a power supply (not shown) and is designed to power a respective semiconductor layer during the x-ray or gamma ray detection process. One skilled in the art will appreciate that each high voltage connection layer should be relatively thin so as to reduce the x-ray absorption characteristics of each connection layer and, in a preferred embodiment, is a few hundred angstroms thick. As will be described in greater detail below, these high voltage electrodes may be affixed to a semiconductor layer through a metallization process.

Referring now to FIG. 7, a cross-sectional view of FIG. 6 taken along line 7-7 thereof illustrates the relative thickness of each semiconductor layer **62**, **64** in one embodiment. In addition, for this embodiment, the pixel pitch and contact size are similar in both layers and about equal to the smaller thickness. Similarly to the high voltage electrode layers **66**, **68**, the 2D contact arrays **67**, **69** should also be minimally absorbent of radiographic energy. Each array or signal collection layer is designed to provide a mechanism for outputting the electrical signals created by the semiconductor layers to a data acquisition system or other system electronics. As explained in more detail later, a mechanism for flexibly combining signals for pixels in different layers is provided. One skilled in the art will appreciate that many (possibly several hundred) interconnects (not shown) are used to connect all the contacts **65** with the CT system electronics. Further, the cumulative 3.0 mm thickness of the semiconductor conversion layer is such that 99% of the x-rays are absorbed. The absorption is calculated with a physics model for an x-ray spectrum typical of a medical CT acquisition, 120.0 kvp spectrum filtered by 20.0 cm.

In addition, as shown in FIG. 7, the thickness of the semiconductor layers **62**, **64** is different from one another but the pixel pitch and contact size is similar. The layers are arranged with a specific order with regard to the x-ray direction so as to leverage the exponential absorption characteristic. For FIG. 7, when the x-rays are incident upward

toward the bottom common contact array, more x-rays are deposited in semiconductor layer **62** than in semiconductor layer **64**. For example, assuming that semiconductor layer **62** has a thickness of one millimeter (mm) and semiconductor layer **64** has a thickness of 2.0 mm, semiconductor layer **62** is expected to absorb about 92% of the x-rays whereas the second semiconductor layer **64** is expected to absorb about 7% of the x-rays. The combined total absorption for the two layers replicates the 99% efficiency of a 3.0 mm layer. One important benefit of the construction compared to 3 mm thick single layer, is a decrease in polarization effects for these two thinner layers. This benefit itself will allow operation with a tenfold increase in flux rate in most practical applications.

In addition, by combining the count response from the two layers with a specific self-correction algorithm, the segmented detector, detector **20a**, may be constructed to provide a tenfold increase in count rate performance relative to a single 3.0 mm thick layer of semiconductor material. Consider, for example, a CT detector, as described herein can be constructed to have a first layer absorbing 92% of the incident x-ray flux and second layer absorbing 7%. As a result, the second layer will saturate at a flux rate at 14x higher than a 3.0 mm thick layer. As the incident flux rate increases, the second layer will saturate or over-range at an x-ray flux more than the x-ray flux required to saturate a 3.0 mm thick layer. This variability in saturation characteristics of multiple layers of a single CT detector allows for the output of an over-ranged layer to be estimated by the effective signal in a non-over-ranged or non-saturated layer. In this regard, a saturation state of a given detector layer is detected and, as a result, signal for the saturated layer, or equivalent 3.0 mm thick layer, is empirically estimated from the output of the non-saturated layer in the detector.

An example of this self-correctability algorithm is that at high count rate above which the first layer is saturated, only the count response from a second layer weighted by its fractional absorption is assigned to that projection for each pixel. At low count rate, a weighted sum of the response from both layers is assigned to the projection for each pixel. A more sophisticated algorithm may combine the signals for the two layers with weighting inverse to their DQE such that as the statistical error in one layer's value grows with increasing count rate, then its value is added to the combined sum with reduced weight.

It is contemplated that a CT detector assembly could be constructed such that each CT detector is constructed with such over-range correctability. However, it is also contemplated that only those detectors in the detector assembly typically associated with over-ranging are constructed with this over-ranging self-correctability. For instance, the periphery detectors of a detector assembly typically encounter higher flux conditions than the more centrally disposed detectors. In this regard, the peripheral detectors can be constructed with over-ranging self-correctability whereas the more centrally located detectors are not. Further, layers with other detection mechanisms and detector materials having high count rate capability, but poor count rate and/or energy response characteristics, can be used in certain parts of the detector to estimate the count rate and energy response of the saturated layer.

Additionally, it is contemplated that a given CT detector may have more than two semiconductor layers. In this regard, the effective signal output of two or more non-saturated layers could be used to estimate the output of the saturated layers. For instance, a detector may be constructed with a first layer that has a 35x effective response, the second

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layer having a 10x effective response, and a third layer with an effective response equivalent to that of the first layer. In this regard, the first and third layers would saturate at higher x-ray flux layers than the second layer. Accordingly, when the second layer has over-ranged or saturated, the output of the first and third layers can be used to compensate or effectively determine the output of the over-ranging second layer.

Referring now to FIG. 8, another contemplated design for a CZT or direct conversion detector is shown. In this embodiment, detector 20b also includes a pair of semiconductor layers 74, 76. In contrast to the previously described embodiment detector 20b includes a single, common signal collection layer or 2D contact array 78. This single, yet common array 78 is designed to collect electrical signals from both semiconductor layers 74, 76 and output those electrical signals to a DAS or other system electronics. In addition, detector 20b includes a pair of high voltage electrodes 80, 82. Each high voltage electrode effectively operates as a cathode whereas the contacts 79 of the 2D array 78 operate as an anode. In this regard, the voltage applied via high voltage connections 80, 82 creates a circuit through each semiconductor layer to the signal collection contacts array 78.

Yet another contemplated embodiment is illustrated in FIG. 9. As shown in this embodiment, detector 20c includes four semiconductor layers 84, 86, 88, and 90. Detector 20c further includes two electrically conductive lines or paths 92, 94 that are electrically connected to high voltage electrodes 87, 89, 91 as well as collection contact arrays 93, 95. Electrically conductive path 92 receives and translates electrical signals from contact arrays 93, 95. In this regard, a single data output is provided to the CT system electronics. Similar to a single signal collection lead, a single high voltage connection 94 is used to power the four semiconductor layers 84-90 via electrodes 87, 89, 91. Detector 20c only requires a single high voltage connection.

Referring to FIG. 10, a monolithic embodiment of the present invention is shown. Similar to the embodiment of FIG. 7, detector 20d includes four semiconductor layers 96-102. Each semiconductor layer 96-102 is connected to a pair of electrically conductive layers. In this regard, one electrically conductive layer is used for application of a voltage whereas the other electrically conductive layer is used for collection of the electrical signals generated by the respective semiconductor layers. To minimize the number of electrically conductive layers, detector 20d utilizes an alternating electrically conductive layer architecture. That is, every other electrically conductive layer is used for high voltage connection with the other electrically conductive layers used for signal collection. In this regard, electrically conductive layers 104, 106, and 108 are used for application of a relatively high voltage whereas layers 110 and 112 include contacts for signal collection. As such, high voltage collection layers 104 and 108 are used to apply a voltage to semiconductor layers 96 and 102, respectively. High voltage connection layer 106 is used to apply a voltage to semiconductor layers 98 and 100.

As described above, in a preferred embodiment, each semiconductor layer is constructed from CZT material. One skilled in the art will appreciate that there are a number of techniques that may be used to construct such a semiconductor. For example, molecular beam epitaxy (MBE) is one method that may be used to grow each thin layer of CZT material. Screen printing of CZT particles in polymeric binder is a potentially low cost, low temperature method of forming layers on a flexible wiring substrate. One skilled in

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the art will appreciate that a number of techniques may be used to metallize the semiconductor layers to provide the electrically conductive connections heretofore described.

Further, metallization may also be used to provide signal feedthroughs for the collection contacts as illustrated in FIG. 11. As shown, a single layer of semiconductor material 114 is sandwiched between an array 116 of collection contacts and a high voltage electrode layer 118. Prior to metallization of the semiconductor layer 114 to form collection contact array 116 and high voltage electrode layer 118, holes 120 may be etched or otherwise formed in semiconductor 114. The holes 120 may then be metallized to provide a signal feed path 122 from a respective collection contact 124. The signal feedthroughs or conductive paths 122 are constructed within holes 120 so as to not be in contact with the near-contiguous high voltage electrode layer 118. In this regard, signal runs may extend vertically or in the x-ray reception direction throughout the detector to a bus (not shown) designed to translate the electrical signals emitted by the individual collection contacts 124 to the CT system electronics. As a result, a stacked arrangement of a series of thin stacked layers in the x-ray direction is formed.

Heretofore, the present invention has been described with respect to a multilayer CT detector designed with different layer thicknesses but similar dimension of the pixel size.

The present invention has been described with respect to a multi-layer CT detector incorporating direct conversion, semiconductor layers with varying thickness to reduce the likelihood of such an energy sensitive CT detector saturating or over-ranging at the x-ray flux rates typically encountered with conventional CT scans. As will be described hereinafter, however, the present invention is also directed to an energy sensitive, over-ranging resistant CT detector that utilizes variability in the electrical contacts of a multi-layer CT detector to improve saturation characteristics of the CT detector.

Referring now to FIG. 12, a side elevational, exploded view of a portion of a CT detector incorporating the present invention is shown. As shown, the detector 126 is formed on a substrate 128 that is secured to a detector frame (not shown) via fasteners (not shown). Substrate 128 supports a pair of detector layers 130 and 132. Each detector layer 130, 132 is composed of a radiation conversion component and a signal collection component. Layers 130, 132, which in the illustrated embodiment, have different thicknesses, are stacked in the x-ray direction 134 and separated from one another by a flex layer 136. The CT detector 126 also includes a high voltage bias wire 138 connected to detector layer 130 to bias the detector assembly.

As referenced above, detector 126 includes a pair of detector layers 130 and 132. The detector layers may comprise scintillator and photodiodes consistent with conventional CT detectors or fabricated from direct conversion semiconductor material, such as CZT, coupled to a number of detector elements or pixels. As illustrated in FIG. 12, detector layer 130 differs from detector layer 132 in the thickness of respective conversion components 140, 142 and the number and size of the respective detector element arrays 144, 146. As illustrated, detector element array 144 has half the pixel pitch, or four times the number of detector elements 148 than detector element array 146 for an equivalent area of the detector. Additionally, the contact area of detector elements 148 is one fourth that of detector elements 150. As will be described, this variation in the detector element arrays within a single CT detector greatly enhances the saturation characteristics of the detector.

By varying the size of the detector elements within a given detector **126**, the charge collection time associated with each layer of the detector is varied. That is, one skilled in the art will readily appreciate that charge collection time decreases as the thickness of a conversion layer decreases and the size of the detector element decreases. That is, the charge collection time of a detector layer is approximately proportional to the thickness of the conversion layer or detector element size, whichever is smaller, divided by the mobility and electric field across the detector layer. The count rate saturation threshold will be larger for smaller pixel size. Furthermore, smaller pixel area implies a higher flux rate saturation threshold relative for a given count rate saturation threshold in proportion to the area reduction. As such, as conversion layer thickness and/or detector element size decreases, the flux rate limit for the corresponding detector layer increases, thereby, improving the saturation characteristics for that layer of the CT detector. This improvement and variability in saturation characteristics allows for a detector to be constructed where some layers withstand higher x-ray flux levels and provide inputs to a self-correctability algorithm.

In the embodiment illustrated in FIG. **12**, the voltage bias wire or lead **138** extends from substrate **128** to direct conversion layer **130**. It is contemplated, however, as shown in FIG. **13** that the high voltage bias wire **138** may be placed on flex layer **136**. Flex layer **136** constitutes a routing layer and is used to connect the individual detector elements **148** to the readout electronics, i.e. DAS and image reconstructor, of the CT scanner **10**. In the embodiment illustrated in FIG. **13**, the high voltage wire **138** may be metallized on surface of flex layer **136** and the detector elements **148** may be metallized on an opposite surface.

FIG. **14** illustrates another orientation of the detector layers **130**, **132** and their respective components relative to one another. As shown, the differences in thickness between direct conversion components **140** and **142** may be varied from that shown in FIG. **12** to achieve different absorption and flux rate characteristics. For example, assuming that detector elements **148** have a pixel size of 0.25 mm and detector elements **150** have a pixel size of 1.0 mm, detector layer **130**, assumed to have a thickness of 0.4 mm, will stop one-half of the x-rays **134** impinged thereon and conversion layer **142**, assumed to have a thickness of 4.6 mm, will stop the other half of x-rays **134** not absorbed by layer **140**. The absorption is calculated with a physics model for an x-ray spectrum typical of a medical CT system, 140 kvp spectrum filtered by 3.0 cm. Relative to a single layer 5.0 mm thick, both detector layers **130**, **132** will each have a two-fold improvement in flux rate capability due to incomplete absorption in each layer individually. Further, layer **130** has $\frac{1}{16}$ the area of a 1.0 mm pixel resulting in 16 \times higher flux rate saturation threshold versus a 1.0 mm pixel. Moreover, the combination of reduced layer thickness and reduced detector element size results in a 4 \times reduced charge collection time for layer **130** relative to a single 5.0 mm detector layer with 1.0 mm pixel size. The flux rate improvements due to each of these mechanisms are multiplicative. As a result, this combination of incomplete absorption (2 \times), smaller area (16 \times) and decreased charge collection time (4 \times), the total flux rate saturation threshold for detector layer **130** may be 128 \times higher relative to a 5.0 mm thick layer with 1.0 mm detector element pitch. Further, layer **130** will have less polarization due to improved charge collection efficiency in the thin layer.

Referring now to FIG. **15**, relative to the embodiment of FIG. **14**, the order of the layered detector has been reversed.

This reversal results in 99% of x-ray absorption in detector layer **132**, which has a detector element pitch of 1.0 mm. As such, only 1% of the x-rays will be left for absorption in detector layer **130**, which has detector element pitch of 0.25 mm. Accordingly, the absorbed flux rate fraction for detector layer **130** is 100 \times less than that of a single layer detector 5.0 mm thick and a pitch of 0.25 mm. Detector layer **132** achieves a 6 \times increase in flux rate capabilities due to 4 \times faster charge collection time and $\frac{1}{16}$ the pixel area. In total, the multi-layer detector has a 6400 \times improvement in flux rate performance compared to a single layer detector 5.0 mm thick and a detector element pitch of 1.0 mm.

Referring now to FIG. **16**, it is contemplated that a detector **126** may be constructed to have more than two detector layers. For example, detector **126** may be designed to have three separate detector layers **130(a)**, **130(b)**, and **132**. For purposes of illustration, the detector of FIG. **16** is oriented similar to that shown in FIG. **15** with the addition of another detector layer. As such, the detector illustrated in FIG. **16** includes a relatively thick conversion layer **140** and two relatively thinner conversion layers **142(a)**, **142(b)**. Moreover, the detector element pitch for detector layer **132** is 4 \times that of detector layers **130(a)** and **130(b)**. It is contemplated that a detector with the configuration illustrated in FIG. **16** will operate differently than the detectors heretofore described.

Specifically, for the detector **126** of FIG. **16**, at lower x-ray flux levels, none of the detector layers will saturate and the data from the smaller detector elements **148(a)** and **148(b)** will be combined to provide a single signal. That is, assuming that the detector elements **148(a)** and **148(b)** are one-fourth the pitch of detector elements **150**, the count data for detector elements **148(a)** and **148(b)** will be binned in a 4 \times 4 manner so as to be equivalent to the pitch of detector elements **150** of detector layer **132**. For intermediate flux levels, detector layer **132** will saturate and count data from detector layers **130(a)** and **130(b)** will only be used. The third layer may be constructed to have a saturation threshold of 1000 \times compared to a 5.0 mm thick, single layer detector assembly having a 1.0 mm detector element pitch.

Specifically, for the detector **126** of FIG. **16**, at lower x-ray flux levels, none of the detector layers will saturate and the data from the smaller detector elements **148(a)** of array **144(a)** and detector elements **148(b)** of array **144(b)** will be combined to provide a single signal. That is, assuming that the detector elements **148(a)** and **148(b)** are one-fourth the pitch of detector elements **150**, the count data for detector elements **148(a)** and **148(b)** will be binned in a 4 \times 4 manner so as to be equivalent to the pitch of detector elements **150** of detector layer **132**. For intermediate flux levels, detector layer **132** will saturate and count data from detector layers **130(a)** and **130(b)** will only be used. The third layer may be constructed to have a saturation threshold of 1000 \times compared to a 5.0 mm thick, single layer detector assembly having a 1.0 mm detector element pitch.

As referenced above, the present invention is directed to achieving improvement in saturation characteristics of a CT detector and assembly using multiple direct conversion layers. The present invention is also directed to achieving improvement in saturation characteristics of the CT detector through reduction of detector element size. Each detector element of a CT detector is commonly referred to as a "pixel" and, as such, in one embodiment, the present invention is directed to the "sub-pixelation" of a pixel area.

Referring now to FIG. **18**, a single pixel area **160** (shown in phantom) is pixelated into four equally sized sub-pixels **162**. In the illustrated example, each sub-pixel **162** is con-

nected to a dedicated readout lead 164. Because flux at a pixel is proportional to its area, the combined flux rate saturation threshold of the four separate sub-pixels 162 is 4× that which would be achieved by a single pixel 160 covering the area of the four sub-pixels 162. In addition, each sub-pixel 162 will have a faster charge collection time because of its reduction in size relative to the layer thickness. Faster charge collection time is indicative of a larger saturation flux rate limit over and above the improvement in count rate performance achieved simply by a reduction in detector element size. It is noted that since each sub-pixel 162 is similarly sized, the sub-pixels will saturate at roughly the same x-ray flux level.

On the other hand and referring to FIG. 19, the area achieved by a single pixel 160 may be pixelated into sub-pixels that have different flux rate characteristics. For example, as shown in FIG. 19, sub-pixel 162(a) is significantly larger than sub-pixel 162(b). This asymmetry in sub-pixel size yields a composite pixel area with different saturation thresholds within the composite pixel area. Specifically, assuming that sub-pixel 162(a) is 20× larger than sub-pixel 162(b), then sub-pixel 162(a) will saturate at an x-ray flux threshold 20× that of sub-pixel 162(b).

It is contemplated that any number of orientations may be implemented to orientate sub-pixel 162(a) relative to sub-pixel 162(b). In the arrangement illustrated in FIG. 20, it is believed that the center placement of sub-pixel 162(b) improves cross-talk characteristics between the sub-pixels. That is, in the illustrated arrangement, sub-pixel 162(b) is less likely to be affected by neighboring sub-pixels and, as such, may be more immune from cross-talk from sub-pixel 162(a) when compared to the arrangement of FIG. 19.

It is recognized that flux rate is not uniform across a CT detector. In this regard, the present invention also includes an x-ray flux management system that detects and/or anticipates saturation of a given portion of a CT detector such that appropriate corrective measures may be taken. For example, it is well-known that the extremities of a CT detector assembly often will receive more x-ray flux than the center portions of the CT detector assembly due to subject and pre-subject filter attenuation profiles. As such, it is contemplated that post-acquisition logic may be used to only use the output of non-saturated channels for image reconstruction. In another embodiment, saturation of given portions of the CT detector assembly is anticipated and, as a result, a binning scheme is established such that those portions of the CT detector expected not to saturate are electrically connected to the scanner's DAS and those portions expected to saturate are not. In yet another embodiment, connectivity of the detector elements to the system DAS is determined on a per view basis during data acquisition. That is, previous view data and other priori information is used to connect the detector elements to the DAS. This scheme provides a dynamic, yet flexible binning of the detector elements during data acquisition. In another embodiment, connectivity of the detector elements to the DAS is controlled in real-time. In this regard, connectivity can be changed during the acquisition of data for a given view such that connections are opened if high photon rate is detected.

Shown in FIG. 21 is a schematic of a group of detector elements or sub-pixels 164 for a given layer or array of detector elements with each sub-pixel 164 electrically routed to a respective data system input 166. In the illustrated example, the group is comprised of four sub-pixels 164 and, as such, four outputs 168 are provided to four data system inputs 166. The four outputs of the 4×4 DAS channels 166 are input to a truth table circuit 170. The output 172 of the

truth table circuit 170 is a linear combination of the four inputs 174 to the truth table circuit 170 depending on whether any of the inputs are saturated. Although each of the sub-pixels illustrated in FIG. 21 is designed to saturate at the same x-ray flux, it is possible given the contour of the subject being imaged and pre-subject filtering for one sub-pixel of the group to saturate without saturation of a neighboring sub-pixel.

The table below sets out a truth table for combining the outputs of the four sub-pixels. In the truth table, a value of "1" is indicative of non-saturation whereas a value of "0" is. As such, if none of the sub-pixels is saturated, a value of "1" will be input to the truth table circuit 170 for each of the sub-pixels. The truth table indicates that in such a circumstance the outputs from all the sub-pixels are considered acceptable and combined to provide a single output for that group of sub-pixels. On the other hand, if channel "A" or, more precisely, the sub-pixel associated with channel "A", saturates, but the other sub-pixels have not, then the sum of the non-saturated channels is output by the truth table circuit and the data associated with the saturated channel is ignored. For instance, assuming a pixel area composed of one sub-pixel that has a higher x-ray flux saturation threshold higher than another sub-pixel within the pixel area, when x-ray flux is low, both sub-pixels provide a valid output that is summed by the truth table circuit to provide a single output comprised of the count data from both sub-pixels. When the x-ray flux reaches a level to saturate only one of the sub-pixels, data from the non-saturated sub-pixel is the only data output by the truth table circuit.

TABLE 1

LOGIC MAP				
A	B	C	D	Output
1	1	1	1	A + B + C + D
1	1	1	0	A + B + C
1	1	0	1	A + B + D
1	1	0	0	A + B
1	0	1	1	A + C + D
1	0	1	0	A + C
1	0	0	1	A + D
1	0	0	0	A
0	1	1	1	B + C + D
0	1	1	0	B + C
0	1	0	1	B + D
0	1	0	0	B
0	0	1	1	C + D
0	0	1	0	C
0	0	0	1	D
0	0	0	0	Flag

It is recognized that a number of techniques may be used to determine saturation of a given sub-pixel. For example, the count rate data for a given sub-pixel may be compared to a threshold and if the count rate determined by the sub-pixel exceeds the threshold, a saturation value of "0" will be input to the truth table circuit for that sub-pixel. For instance, if the detector system is designed to count photons using direct conversion detectors with a one million count per second saturation threshold, then this threshold would be the threshold level imposed on each sub-pixel, or some percentage thereof to provide a margin less than the saturation threshold.

It is also contemplated that a flexible binning of sub-pixels within a given pixel area, such as that described above, may be achieved to further enhance the ability of the detector to output photon count data despite saturation of

some portions of the detector. That described with respect to FIG. 21 was a signal management scheme that utilized a single DAS channel for each sub-pixel. However, given the number of sub-pixels within a single CT detector, a single DAS channel per sub-pixel may not be feasible. Accordingly, the present invention also contemplates a signal control scheme that utilizes one DAS channel for a group of sub-pixels. In this regard, the number of DAS channels needed may be equivalent to that needed for a CT detector not incorporating sub-pixelation.

Referring now to FIG. 22, a switch network-based signal management system is shown whereupon more than one sub-pixel is dynamically controlled to be connected to a DAS input channel. In this regard, the output of each sub-pixel 164 of a given group of sub-pixels is input to a switch network 176. The switch network is designed to reconnect the outputs of the sub-pixels based on a saturation state of the sub-pixels. The switch network may utilize a truth table to dynamically control connectivity of the sub-pixel output. For those sub-pixels that have saturated, the switch network will discard them such that only non-saturated data is included in output 180.

For example, at low x-ray flux, none of the sub-pixels will saturate and, as such, the output 168 from all the sub-pixels 164 will be combined into a single output 180 that is input to DAS 182. DAS 182 includes a signal shaper 184 constructed to extract single photon events from the output of the switch network. It is recognized that a low-noise/high speed charge amplifier (not shown) may be connected to receive the output of the switch network. The output of the amplifier is then input to signal shaper 184. Signal shaper 184 provides an input to an energy level discriminator 186. Energy level discriminator 186 is connected to signal shaper 184 and is designed to filter photons based on their energy level relative to one or more thresholds. To this end, those photons having energy levels outside a desired range are excluded from counting and processing for image reconstruction. Minimally, discriminator 186 is designed to exclude those photons having an energy level corresponding to noise in the system. It is contemplated that multiple thresholds may be used to define energy level ranges. Counting register 188 receives those photons not filtered out by energy level discriminator 186 and is constructed to count the number of photons received at the detector and provide a corresponding output.

DAS 182 counts the number of photons for the given pixel area 165 comprised of the given sub-pixels 164. Since the switch network will not connect the output of a given sub-pixel if it has saturated, DAS will determine a photon count only from the non-saturated sub-pixels. While only four sub-pixels are shown, it is contemplated that a given pixel area may be sub-pixelated into less or more than four sub-pixels.

Two switch states are illustrated in FIGS. 23 and 24. As show in FIG. 23, if sub-pixel identified with input "A" is not saturated and all other sub-pixels have saturated, then the output of sub-pixel "A" will only be used for photon counting. As shown in FIG. 24, the switch network may combine any combination of sub-pixel outputs, such as sub-pixels "A" and "C" if those are the only non-saturated sub-pixels.

Referring now to FIG. 25, package/baggage inspection system 190 incorporating a detector consistent with described herein is shown. System 190 includes a rotatable gantry 192 having an opening 194 therein through which packages or pieces of baggage may pass. The rotatable gantry 192 houses a radiation source 196 as well as a

detector assembly 198. A conveyor system 200 is also provided and includes a conveyor belt 202 supported by structure 204 to automatically and continuously pass packages or baggage pieces 206 through opening 194 to be scanned. Objects 206 are fed through opening 194 by conveyor belt 202, imaging data is then acquired, and the conveyor belt 202 removes the packages 206 from opening 194 in a controlled and continuous manner. As a result, postal inspectors, baggage handlers, and other security personnel may non-invasively inspect the contents of packages 206 for explosives, knives, guns, contraband, etc.

An x-ray detector module is disclosed that includes a stacked sequence of two or more x-ray detection layers, each containing an electrical contact array. Interposed between the detection layers is an electrical routing material for connecting contacts on the converter layer to readout electronics. The number and thickness of the layers, and the pixel size on each layer is constructed to improve the count rate fidelity and resolution of the imaging system. In one embodiment, the top (most proximate to the x-ray source) layer is thinner so as to stop only a fraction of the incident x-rays. X-rays passing through the first layer are stopped in one of the subsequent layers. Each module containing a sequence of layers is able to accommodate a higher flux without saturation than an equivalent detector with one layer of equivalent stopping power. The first layer, being thin and less susceptible to cross-talk, will also be capable of higher resolution imaging with smaller pixels.

Additionally, it is disclosed that the signal from several sub-pixels making up a composite pixel area may be weighted and combined in a dynamic and real-time configurable manner into a single input channel of a DAS. The configuration is chosen so as to include as many sub-pixels inputs from a composite pixel unit, but to also insure that the DAS channel is not saturated and that the sub-pixels included are not saturated or corrupted. This is particularly advantageous where the sub-pixels, which make up the composite pixel area, have dissimilar saturation thresholds with respect to x-ray flux rate. For example, a detector element comprised of two sub-pixels, one with relatively larger coverage area and another with a relatively smaller coverage area, will have differing saturation characteristics across the cumulative coverage area due to area ratio and small pixel effect increase in the charge collection time.

It is also disclosed that with a detector composed of superimposed layers it is possible to combine signal from sub-pixels in one layer with those of another layer but in a way that excludes saturated or otherwise corrupted sub-pixels. Four exemplary control configurations are disclosed: (1) DAS-per-channel whereupon post-acquisition logic adds only non-saturated channels to digital output; (2) Static, flexible binning, connectivity of sub-pixels to DAS established before acquisitions based on expected flux level based on a priori information; (3) Scan-Dynamic, flexible binning, sub-pixelation connectivity for each view established during scan acquisition based on previous view data and a priori information; and (4) View-Dynamic, flexible binning, sub-pixelation connectively changed during a view starting with expected best case (e.g. starts with maximal connectivity and removes connections if high photon rate detected).

Therefore, the present invention includes a CT detector. The CT detector includes a first direct conversion layer having a first array of electrical contacts and constructed to directly convert radiographic energy to electrical signals representative of energy sensitive radiographic data. The first direct conversion layer is also designed to saturate at a first saturation threshold. The CT detector further includes a

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second direct conversion layer having a second array of electrical contacts and constructed to directly convert radiographic energy to electrical signals representative of energy sensitive radiographic data. The second direct conversion layer is designed to saturate at a second saturation threshold different from the first saturation threshold.

The present invention also includes a radiographic imaging system having a radiation source to project radiographic energy toward a subject to be scanned and a detector assembly to receive radiographic energy from the radiation source and attenuated by the subject. The detector assembly includes an array of detectors whereby each detector is designed to provide photon count and/or energy discriminatory output. The imaging system also includes a computer programmed to detect over-ranging in a section of a given detector and determine output for the over-ranging section of the given detector from non-over-ranging sections of the given detector.

The present invention further includes a CT scanner having a rotatable gantry with an opening to receive an object to be scanned. The CT scanner also includes an x-ray source configured to project x-rays toward the object as well as a detector array having a plurality of detectors designed to provide energy sensitive output in response to detected x-rays. A data acquisition system is connected to the detector array and configured to receive the detector outputs. The CT scanner also includes an image reconstructor connected to the DAS and configured to reconstruct image of the object from the detector outputs received by the DAS. The CT scanner further includes means for determining an output for a given detector of the detector array when a portion of the detector has reached an x-ray saturation state.

The present invention has been described in terms of the preferred embodiment, and it is recognized that equivalents, alternatives, and modifications, aside from those expressly stated, are possible and within the scope of the appending claims.

What is claimed is:

1. A CT scanner comprising:

- a rotatable gantry having an opening to receive an object to be scanned;
- an x-ray source configured to project x-ray photons toward the object;
- a detector array having a plurality of detectors designed to provide energy sensitive output in response to detected x-ray photons, the energy sensitive output separately indicating at least one of a number of x-ray photons detected or an energy level of x-ray photons detected;
- a data acquisition system (DAS) connected to the detector array and configured to receive the detector outputs;
- an image reconstructor connected to the DAS and configured to reconstruct an image of the object from the detector outputs received by the DAS; and
- means for determining an output for a given detector of the detector array when a portion of the given detector has reached an x-ray saturation state.

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2. The CT scanner of claim 1 wherein the given detector includes multiple electrical contacts, each electrical contact designed to provide a photon count and/or energy discriminatory output to a channel of the DAS.

3. The CT scanner of claim 2 further comprising means for ignoring the output of an electrical contact of the given detector if that electrical contact has reached an x-ray saturation state.

4. The CT scanner of claim 3 further comprising means for executing a truth table to determine which electrical contact outputs to combine and input to the channel of the DAS.

5. The CT scanner of claim 1 wherein each detector includes a plurality of semiconductor layers designed to directly convert x-rays into electrical signals.

6. The CT scanner of claim 5 wherein the plurality of semiconductor layers includes a first layer and a second layer thinner than the first layer.

7. The CT scanner of claim 6 wherein the first layer is constructed to saturate before the second layer.

8. The CT scanner of claim 6 further comprising means for reading-out outputs from the first semiconductor layer and second semiconductor layer simultaneously.

9. The CT scanner of claim 8 wherein the means for reading-out includes a readout layer sandwiched between the first and the second semiconductor layers.

10. The CT scanner of claim 5 wherein the means for determining includes means for detecting saturation of a given semiconductor layer and means for using output of a non-saturated semiconductor layer to correct saturation of the given semiconductor layer.

11. The CT scanner of claim 1 wherein the given detector includes a capability for both CT and SPECT.

12. A shared detector CT/SPECT scanner comprising:
 a rotatable gantry having an opening to receive an object to be scanned;
 an x-ray source configured to project x-ray photons toward the object;
 an interchangeable collimator to provide focus either for radiation emission from the object or a focal spot of the x-ray source;
 a detector array having a plurality of detectors designed to provide energy sensitive output in response to detected x-ray photons, the energy sensitive output separately indicating at least one of a number of x-ray photons detected or an energy level of x-ray photons detected;
 a data acquisition system (DAS) connected to the detector array and configured to receive the detector outputs;
 an image reconstructor connected to the DAS and configured to reconstruct an image of the object from the detector outputs received by the DAS; and
 means for determining an output for a given detector of the detector array when a portion of the given detector has reached an x-ray saturation state.

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