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(54) Title: TWO-DIMENSION, HIGH SPATIAL RESOLUTION DETECTOR OF THERMAL AND SUBTHERMAL NEUTRONS BASED ON CCD AND CMOS ELECTRONIC SENSORS, AND A CONVERTER CONTAINING GADOLINIUM

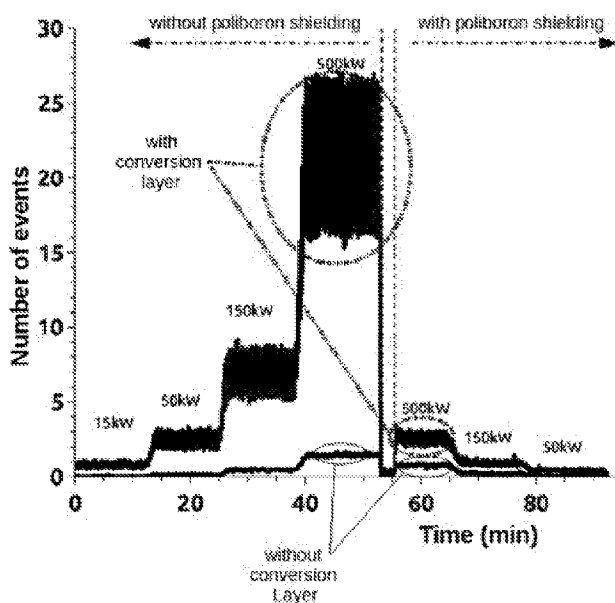


Fig. 4

(57) Abstract: A detector of thermal and subthermal neutrons with high spatial resolution in two dimensions, based on an electronic image forming sensor (for example a CCD or CMOS device). The detector possesses as small size, low consumption, is portable and of very low cost. The detector does not utilize the scarce and expensive ^3He isotope, and be mass-produced. It can be used for defense, security, and control posts in borders and traffic, detecting the presence of fissile materials, such as plutonium or uranium; in dosimetry in radiotherapy treatments based on the use of neutrons; and in various techniques which employ neutron beams for numerous basic and applied studies, among other applications. It also has environmental applications, controlling contamination by

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TWO-DIMENSION, HIGH SPATIAL RESOLUTION DETECTOR OF THERMAL
AND SUBTHERMAL NEUTRONS BASED ON CCD AND CMOS ELECTRONIC
SENSORS, AND A CONVERTER CONTAINING GADOLINIUM

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FIELD OF THE INVENTION

The present invention refers to a device that allows for detecting and
10 recording, in two dimensions and with high spatial resolution in two dimensions,
thermal or subthermal neutrons based on an image sensor using CMOS and/or CCD
technologies and a conversion gadolinium-containing layer. The field of application is
nuclear industry, neutron instrumentation, medicine, radiotherapy by boron neutron
capture (BNCT) or gadolinium neutron capture (GdNCT), environment monitoring,
15 radiological security, mining prospecting (for uranium, among others), oil prospecting,
nuclear safeguards, security control in customs portals and traffic (both by obtaining
neutronic images and by detection of fissile elements).

BACKGROUND OF THE INVENTION

20 There exist different thermal neutron detectors based on the detection of
secondary particles which are generated after absorption of a thermal neutron by a given
isotope. A type of detector often used is based on an ionizing chamber or proportional
counter containing ^3He , a gas sensible to neutrons. Due to the high effective neutron
capture section in ^3He , these detector also possess a high detection efficiency. In recent
25 years, the generalized use of these type of detectors in security control systems have

depleted most of the world stock of the ^3He isotope, leading to a “ ^3He crisis”, consisting in a great reduction of availability of this resource. This situation has resulted in an increment of up to 10 times or more in ^3He price over the last decade. There also exist detectors based on ionizing chambers over which layers or multilayers of isotopes such as ^{10}B or ^{235}U are laid on. These type of detectors require a considerably large volume, and hence do not allow for detecting particles with a high spatial resolution.

Other types of detectors have been proposed which are based on detecting secondary particles that occur after the capture of a thermal neutron in the ^{10}B isotope. For this purpose, electronic sensors of the CCD (Charged Coupled Devices) or CMOS (Complementary Metal–Oxide–Semiconductor) type are used, covered by a conversion layer containing ^{10}B . However, these have the disadvantage of low neutron detection efficiency. This is primarily due to the fact that, in spite of the effective neutron capture section of the ^{10}B being sufficiently high, the particles emitted by the conversion layer (alpha particles of up to 1.78 MeV) have a very small range in the materials forming the detector and in the conversion layer itself. This poses a narrow limit to the maximum thickness of the conversion layer (a few microns), and in some cases it cannot be used on electronic devices which comprise insulation layers such as Field Oxides in a CMOS device, as these would completely stop the alpha particles. An example of it is patent US 6,262,421 B1 in which, when a neutron is captured in the conversion layer, an alpha particle is generated, which can then be detected by the solid state sensor.

Another proposal is that of patent WO 2013032549 A1 which proposes using a gadolinium layer as a converter of neutrons into charged particles, and then detecting the charged particles using the transient change in the current of a

semiconductor transistor. The difference with said patent is that the present invention uses an image sensor based on a pixels array formed by P-N junctions, or a pixels array built on CCD technology, in which detection is not based on the measurement of current in a transistor but through gathering of charge generated in one or more pixels of the sensor. This represents an important advantage over patent WO 2013032549 A1 since it allows for having a larger detection area, lower power consumption, simpler reading electronics, and also allows for having the detector in a state sensitive to neutrons at all times, even with a very large number of detecting elements simultaneously active (several millions).

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The present invention is also different from the previous inventions of neutron detectors in that the device of the present invention allows obtaining a high spatial resolution in two dimensions (formation of neutronic images) that cannot be achieved with other existing techniques. Furthermore, it utilizes a commercial 2D sensor which is available at low cost, in combination with a gadolinium containing layer, an approach which has not been carried out nor proposed in prior art devices or patents.

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On the other hand, the use of scintillator conversion layers, which emit visible light after capturing a neutron, has been proposed. The difference with the present invention is that the image sensor described herein allows for detecting electrons instead of visible light as in the other patents. Patent application DE19644522A1 proposes a neutron detector in which a gadolinium-containing scintillator layer is used. Patent US 5,334,840 A proposes a hexagonal array of gadolinium layers which would emit more light thereby increasing sensibility. Patent application US20080067394A1 proposes a scintillator system which by means of temporal coincidence between two signals allows for detecting neutrons or gamma photons, identifying which particle

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arrived. Patent US 5,734,166 A shows a gamma scintillator covered by a scintillator conversion layer which allows for detection of neutrons. Regarding these detectors, the present invention allows for reducing the detector size, providing a greater spatial resolution in neutrons detection.

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BRIEF DESCRIPTION OF THE INVENTION

It is therefore an object of the present invention to provide a device which allows for detecting and recording in two dimensions, with high spatial resolution, thermal and/or subthermal neutrons based on an image sensor using CMOS and/or CCD technologies, and a gadolinium-containing conversion layer. The image sensor detects the particles generated in the gadolinium-containing layer, which result from the capture of neutrons. The image sensor may be any CMOS (Complementary Metal-Oxide Semiconductor) image sensor, such as for example a sensor based on active pixels, an array of passive photodiodes, or a CCD (Charge-Coupled-Devices) image sensor.

Consequently, it is an object of the present invention to provide a subthermal and thermal neutron detector, comprising a semiconductor device sensitive to charged particles and to electromagnetic radiation, and a conversion layer which converts neutrons into charged particles and electromagnetic radiation, said conversion layer containing some form of gadolinium, wherein said semiconductor device sensitive to charged particles detects the particles emitted by the gadolinium upon capturing a neutron.

In a preferred embodiment of the present invention, said semiconductor device is an image sensor based on CMOS, CCD, SPiM, or an array of any other type of semiconductor detectors.

In a preferred embodiment of the present invention, the size of the detectors
5 allows for a high spatial resolution for obtaining neutronic images, and wherein the neutrons strike on the front and/or on the rear part of the sensor.

In a preferred embodiment of the present invention, the gadolinium-containing conversion layer shields the semiconductor device from damage due to neutron.

10 A further object of the present invention is to provide the use of two or more semiconductor devices, or a portion of the pixel array of one or more devices, such as those previously mentioned, wherein at least one of the semiconductor devices or portion of the pixel array comprises a gadolinium-containing conversion layer for simultaneously measuring the flux of neutrons and other particles, and a second device
15 or fraction of the pixel array of one or more devices does not have a conversion layer and is mostly sensitive to other particles, wherein the use is for estimating the flux of neutrons and other particles in beams of mixed radiation .

It is yet another object of the present invention to provide a method for estimating the flux of neutrons and other particles in beams of mixed radiation, the
20 method comprising the steps of:

- a) simultaneously measuring the flux of neutrons and other ionizing particles with at least one semiconductor device or portion of a pixel array comprising a gadolinium-containing conversion layer;

- b) measuring the flux of ionizing particles different from neutrons with a second device or fraction of a pixel array of one or more devices which not have a conversion layer; and
- c) calculating the flux of neutrons from the difference between the number of particles detected by each semiconductor device.

DESCRIPTION OF THE DRAWINGS

For greater clarity and comprehension of the object of the present invention, it has been illustrated in various figures, in which the same has been represented in a preferred embodiment, as an example, in which:

Figure 1 is an image of a possible implementation, in which paint containing gadolinium oxide has been laid on the conversion layer.

Figures 2a and 2b show images of sensors mounted on the lid of a dark box (a) and placed in the path of the neutron radiography beam of reactor RA6 (b).

Figure 3a shows an optic image, obtained by exposing the sensor to visible light, showing the zone covered by the Gd-containing conversion layer (in black, due to absorption/dispersion of the light in the conversion layer with gadolinium).

Figure 3b shows an image formed by the events recorded during the irradiation with neutrons, showing the sensitivity of the region covered with Gd. Each white point represents one or various events. It can be observed that, in the region covered by the conversion layer, a high number of events caused by the capture of neutrons in the conversion layer have been detected.

Figure 4 is a graph showing events per frame recorded in the detector. Two sensors are compared: a control sensor sensitive only to gamma photons, and the sensor with the Gd-conversion layer sensitive to neutrons.

DETAILED DESCRIPTION OF THE EMBODIMENT EXAMPLE

Making reference to the figures, it is observed that Figure 1 presents a successfully tested prototype, in which a commercially available CMOS image sensor (2) arranged on a circuit board (3) has been partially covered with a conversion layer (1) made of 50% gadolinium oxide and 50% synthetic varnish, forming a gadolinium-containing layer, which adheres to the sensor (Figure 1). The device is read with a computer and video acquirer, such as described in patent application 20150102319.

The sensor of Figure 1 was exposed to a flux of neutrons and photons in the neutron radiography beam of the RA6 Reactor, Centro Atómico Bariloche, CNEA. Besides said partially covered sensor of Figure 1, another identical sensor without the gadolinium conversion layer was used as the control device. As observed in Figure 2a, the two sensors were mounted in a dark chamber (4) using suitable fixing means (5), to prevent light from entering, and where placed in the beam of the previously mentioned RA6 (as observed in Figure 2b). In order to reduce the flux of gamma photons coming from the reactor core (relative to that of the neutrons) a shielding of 10 cm of lead was interposed in the beam between the reactor core and the sensors. The two sensors were exposed to growing neutron influxes, which was achieved by increasing the reactor power.

Figure 3a shows an optic image of the sensor partially covered by the conversion layer. The dark part of the image is the covered part of the sensor. Figure 3b shows the total of registered events when the irradiation in the neutron beam occurs. A larger number of recorded events is observed in the region having the conversion layer, while in the non-covered region a lower number of events generated by gamma photons is observed.

Finally, Figure 4 shows the mean amount of recorded events per frame (1/25s) in the sensor covered by the conversion layer, and the amount of recorded events in the same lapse in the sensor without a conversion layer (device used as control).
5 During measurement the flux of neutrons was increased varying the power of the reactor: 15 Kw, 50 Kw, 150 Kw, and 500 Kw. It can be seen that the sensor including the gadolinium conversion layer detects a larger number of events due to the nuclear reactions originated by neutrons. Then a layer of 10 cm of borated polyethylene, which has an attenuation of thermal neutrons larger than the attenuation of gamma photons,
10 was interposed between the device and the beam. This results in the number of counts in the sensor with the conversion layer being much smaller than the number of detected counts in the control sensor. Between the minutes 52 and 56 the flux of particles was interrupted interposing a 40cm Pb shield.

15 As previously mentioned, the object of the present invention consists of a neutron detector formed by a gadolinium-containing conversion layer and an electric sensor which can be a solid state image sensor with CCD and/or CMOS technologies. The gadolinium-containing conversion layer captures neutrons and, by means of nuclear reaction $^{157}\text{Gd} (n,\gamma) ^{158}\text{Gd}$, emits quasi instantaneous gamma photons, conversion
20 electrons, and Auger electrons of tens of KeV. The solid state image sensor, which can be a CMOS image sensor built ad-hoc, a commercial CMOS sensor such as the one of patent application 20150102319, a CCD sensor or any other, detects the electrons generated by the reaction in the conversion layer, allowing for detection of the incident neutron. Another possible type of detector is the silicon photomultiplier (SiPM).

The gadolinium may be in its natural isotopic composition, or may be enriched in the ^{157}Gd isotope. Natural or ^{157}Gd -enriched gadolinium may be part of different compounds and materials which simplify its application, deposition, and/or arrangement on the sensor surface, such as paints, varnishes, etc. In the prototype of the exemplary embodiment, gadolinium oxide powder has been mixed with synthetic
5 varnish, or with photo-resins using photolithography.

The detector of the present invention has the advantages of utilizing as a conversion layer a widely-available material, as well as allowing for a sensor of small size, high spatial resolution, low cost and ease of construction. In this sense it possesses
10 an important advantage over the sensors which use ^3He , ^{235}U , etc. as conversion materials

Furthermore, since ^{157}Gd possesses an effective capture cross section much larger than that of ^{10}B , the present invention allows for a greater efficiency in the capture of incident neutrons with relatively thin layers (tens of microns). That thickness is also
15 smaller than the range of the electrons generated when ^{157}Gd captures a neutron, further favoring that those electrons exiting the layer will be recorded by the electronic sensor.

The simultaneous use of two detectors, one covered with the gadolinium-containing conversion layer and another without it, allows for measuring the sum fluxes of neutrons and other ionizing particles in the first sensor, and only the ionizing particles
20 different from neutrons in the second sensor. The fluxes of neutrons and other particles in a beam of mixed radiation can be determined through the difference between the number of particles detected.

Finally, the high spatial resolution in two dimensions that can be obtained if
25 the detector used is for example a CMOS image sensor or a CCD image sensor could

allow for neutron microscopy, allowing analyzing for example emissions and transmissions of neutrons in samples of small size. The potential resolution that can be obtained is the size of the pixel, in the order of $10\mu\text{m}$.

CLAIMS

Having this specially described and determined the nature of the present invention and how it is to be carried out, it is declared to claim as property and exclusive right:

5 1. A subthermal and thermal neutron detector, comprising a semiconductor device sensitive to charged particles and to electromagnetic radiation, and a conversion layer which converts neutrons into charged particles and electromagnetic radiation, said conversion layer containing some form of gadolinium, wherein said semiconductor device sensitive to charged particles detects the particles emitted by the gadolinium
10 upon capturing a neutron.

 2. The detector according to claim 1, wherein said semiconductor device is an image sensor based on CMOS, CCD, SPiM, or an array of any other type of semiconductor detectors.

15 3. The detector according to claims 1 or 2, wherein the size of the detectors allows for a high spatial resolution for obtaining neutronic images, and wherein the neutrons strike on the front and/or on the rear part of the sensor.

20 4. The detector according to anyone of claims 1 to 3, wherein the gadolinium-containing conversion layer shields the semiconductor device from damage due to neutron.

 5. The use of two or more semiconductor devices, or a portion of the pixel
25 array of one or more devices, such as those employed in the detector of claim 1, wherein

at least one of the semiconductor devices or portion of the pixel array comprises a gadolinium-containing conversion layer for simultaneously measuring the flux of neutrons and other particles, and a second device or fraction of the pixel array of one or more devices does not have a conversion layer and is mostly sensitive to other particles,
5 wherein the use is for estimating the flux of neutrons and other particles in beams of mixed radiation .

6. A method for estimating the flux of neutrons and other particles in beams of mixed radiation , the method comprising the steps of:

- 10 a) simultaneously measuring the flux of neutrons and other ionizing particles with at least one semiconductor device or portion of a pixel array comprising a gadolinium-containing conversion layer;
- b) measuring the flux of ionizing particles different from neutrons with a second device or fraction of a pixel array of one or more devices which
15 not have a conversion layer; and
- c) calculating the flux of neutrons from the difference between the number of particles detected by each semiconductor device.

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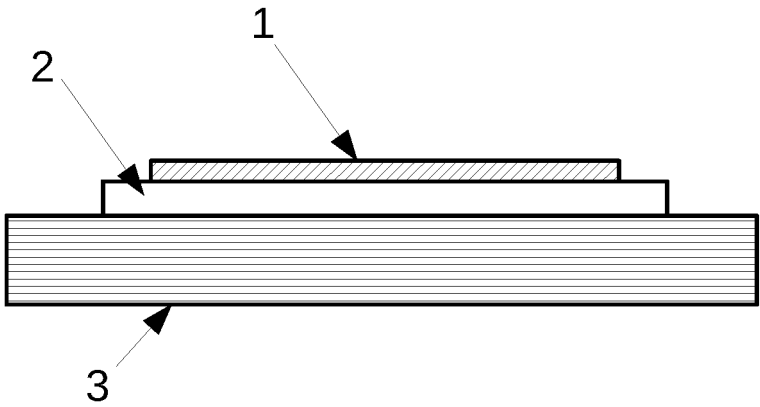


Fig. 1

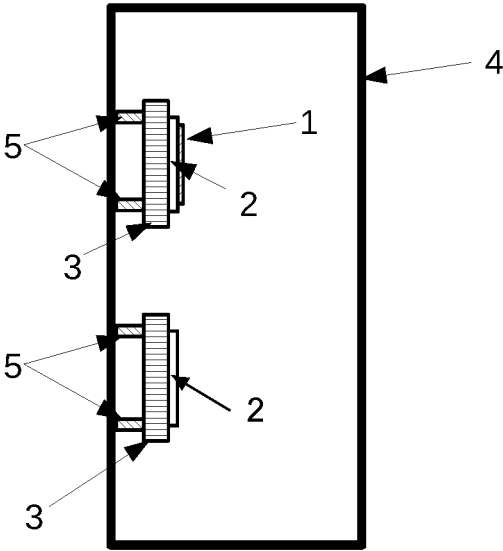


Fig. 2a

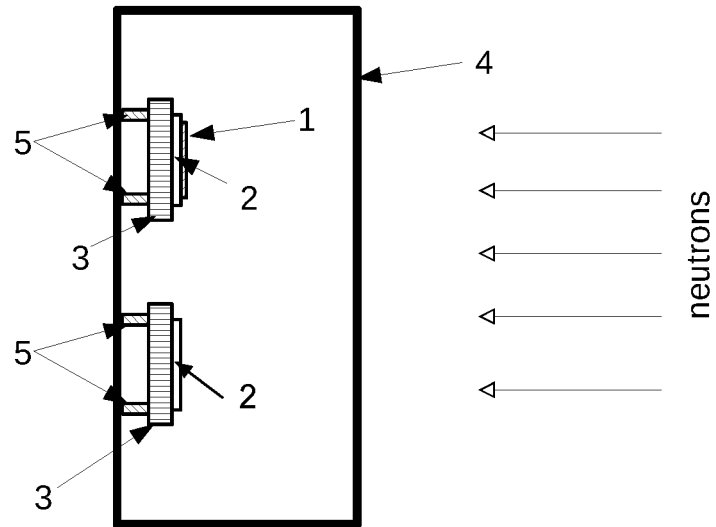


Fig. 2b

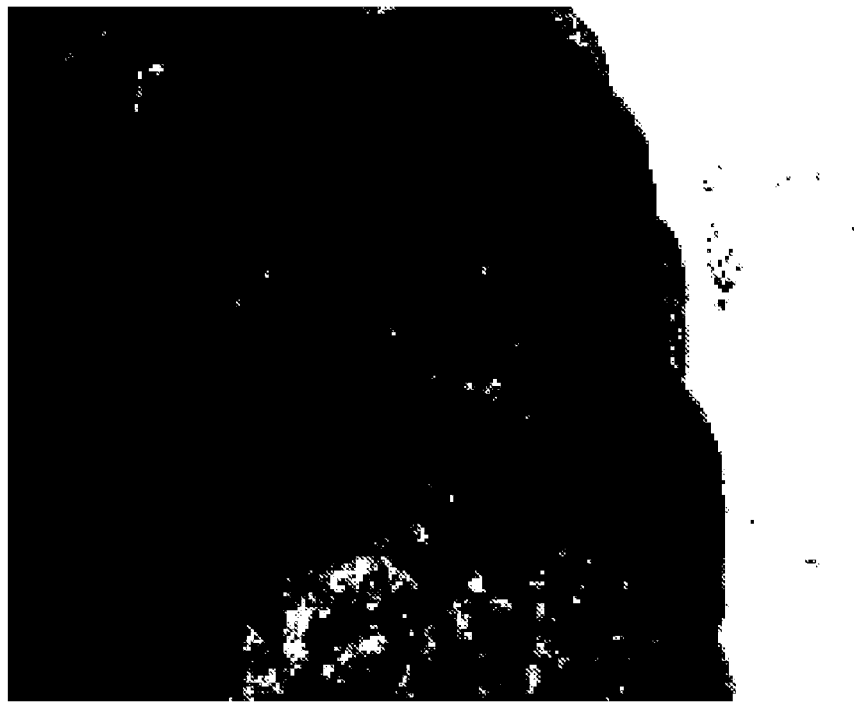


Fig. 3a

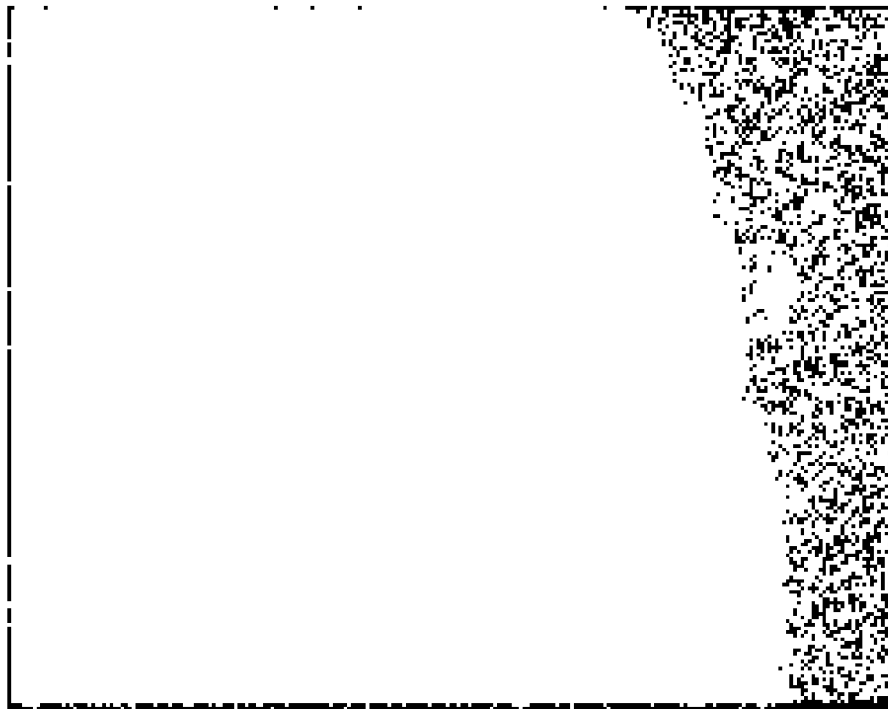


Fig. 3b

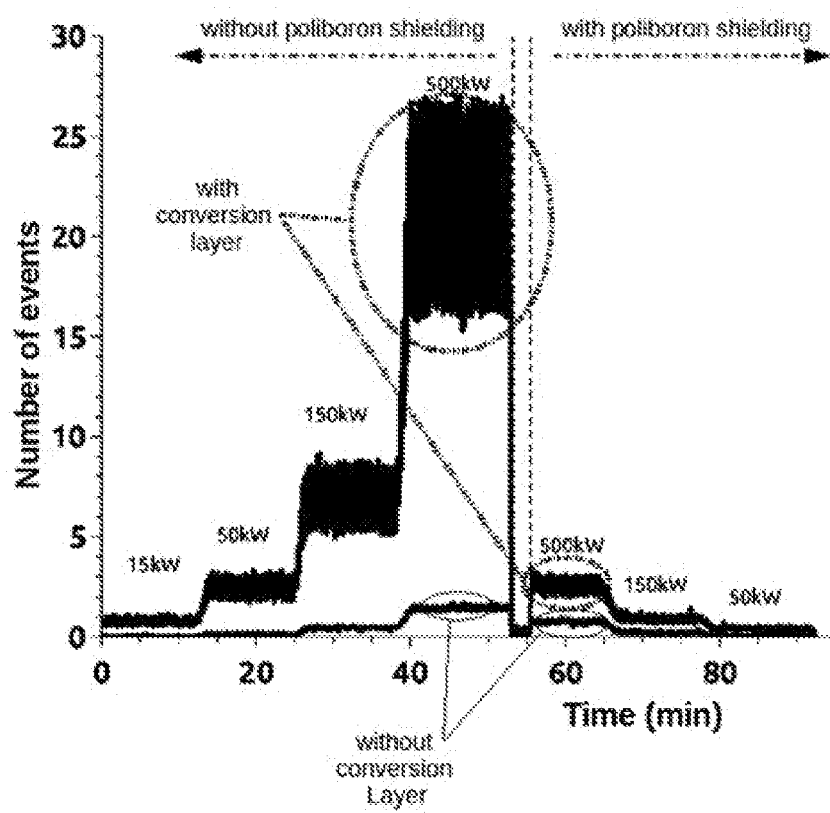


Fig. 4

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2017/053506

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01T3/08
ADD.

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)
G01T

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

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

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2014/079171 A1 (ROY ANSHUMAN [US]) 20 March 2014 (2014-03-20)	1-4
A	paragraphs [0081], [0082], [0096]; figures 4,5A,6A,B,8,9	5,6
X	----- EP 1 531 344 A1 (SCHERRER INST PAUL [CH]) 18 May 2005 (2005-05-18)	1,3
	paragraphs [0016], [0017], [0020], [0021]; figure 1	
X	----- US 2015/053863 A1 (CAO LEI [US]) 26 February 2015 (2015-02-26)	5,6
	paragraphs [0035], [0039], [0041], [0046], [0053], [0054], [0068]; figures 1-3	
	----- -/-	



Further documents are listed in the continuation of Box C.



See patent family annex.

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"&" document member of the same patent family

Date of the actual completion of the international search

8 September 2017

Date of mailing of the international search report

21/09/2017

Name and mailing address of the ISA/

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INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2017/053506

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2012/146415 A2 (FINPHYS OY [FI]; ORAVA RISTO [FI]; SCHULMAN TOM [FI]; MEHTAELAE PETTER) 1 November 2012 (2012-11-01)	1,2
A	page 7, lines 25-30; figures 1A,B,4,8 page 12, line 21 page 13, line 19 - page 14, lines 10-18 page 15, line 17 page 9, lines 6-19 -----	5,6

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

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		US 2014077089 A1	20-03-2014
		WO 2012146415 A2	01-11-2012
