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(54) **PACKAGING METHODS OF SEMICONDUCTOR X-RAY DETECTORS**

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(63) Continuation of application No. 16/830,437, filed on Mar. 26, 2020, now Pat. No. 10,866,330, which is a (Continued)

(51) **Int. Cl.**
G01T 1/24 (2006.01)
H01L 27/146 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC .... ***G01T 1/244*** (2013.01); ***G01T 1/24*** (2013.01); ***G01T 1/247*** (2013.01); (Continued)

(58) **Field of Classification Search**
CPC .... H01L 27/14636; H01L 27/14663; H01L 27/1469; H01L 24/97; H01L 25/042; (Continued)

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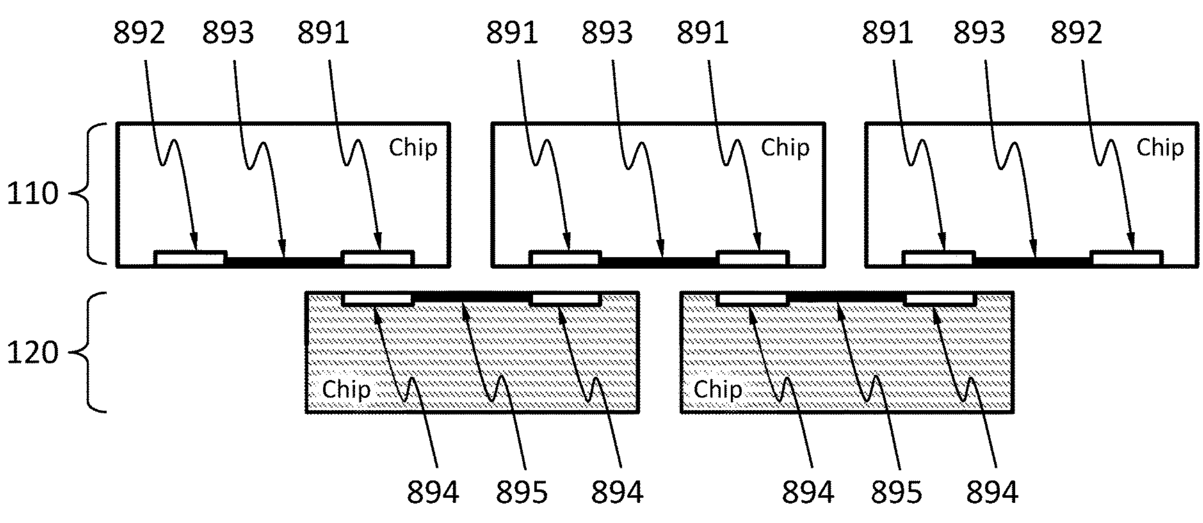
(74) *Attorney, Agent, or Firm* — IPro, PLLC; Qian Gu

(57) **ABSTRACT**

Disclosed herein is a method for making an apparatus suitable for detecting X-ray, the method comprising: obtaining a wafer and a substrate; wherein the substrate comprises an X-ray absorption layer comprising a first plurality of electrical contacts; wherein the wafer has multiple dies and comprises an electronic layer comprising a second plurality of electrical contacts and an electronic system configured to process or interpret signals generated by X-ray photons incident on the X-ray absorption layer; aligning the first plurality of electrical contacts to the second plurality of electrical contacts; mounting the wafer to the substrate such that the first plurality of electrical contacts are electrically connected to the second plurality of electrical contacts; wherein the substrate further comprises a transmission line electrically bridging at least some of the dies; wherein the second plurality of electrical contacts are configured to feed the signals to the electronic system.

18 Claims, 45 Drawing Sheets



Related U.S. Application Data

continuation of application No. 15/737,802, filed as application No. PCT/CN2015/096192 on Dec. 2, 2015, now Pat. No. 10,641,911.

(51) **Int. Cl.**
H01L 23/498 (2006.01)
H01L 23/66 (2006.01)

(52) **U.S. Cl.**
CPC ***H01L 23/49838*** (2013.01); ***H01L 23/66*** (2013.01); ***H01L 27/1469*** (2013.01); ***H01L 27/14618*** (2013.01); ***H01L 27/14636*** (2013.01); ***H01L 27/14661*** (2013.01); ***H01L 27/14663*** (2013.01); *H01L 2224/48091* (2013.01)

(58) **Field of Classification Search**
CPC H01L 25/0655; H01L 25/072; H01L 25/0753; G01T 1/247; G01T 1/24
See application file for complete search history.

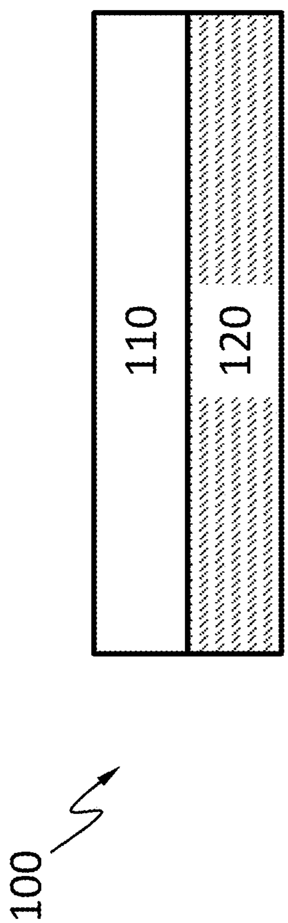


Fig. 1A

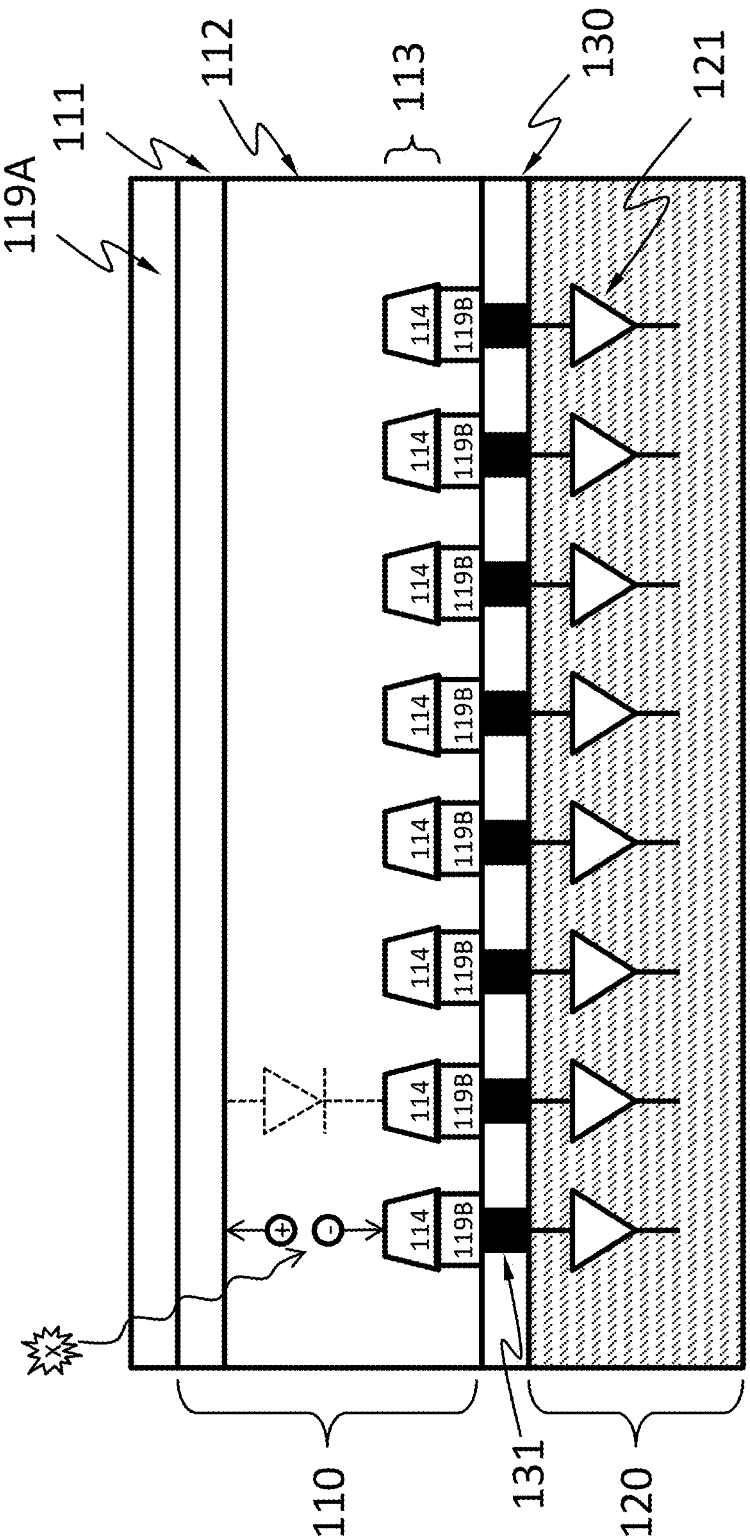


Fig. 1B

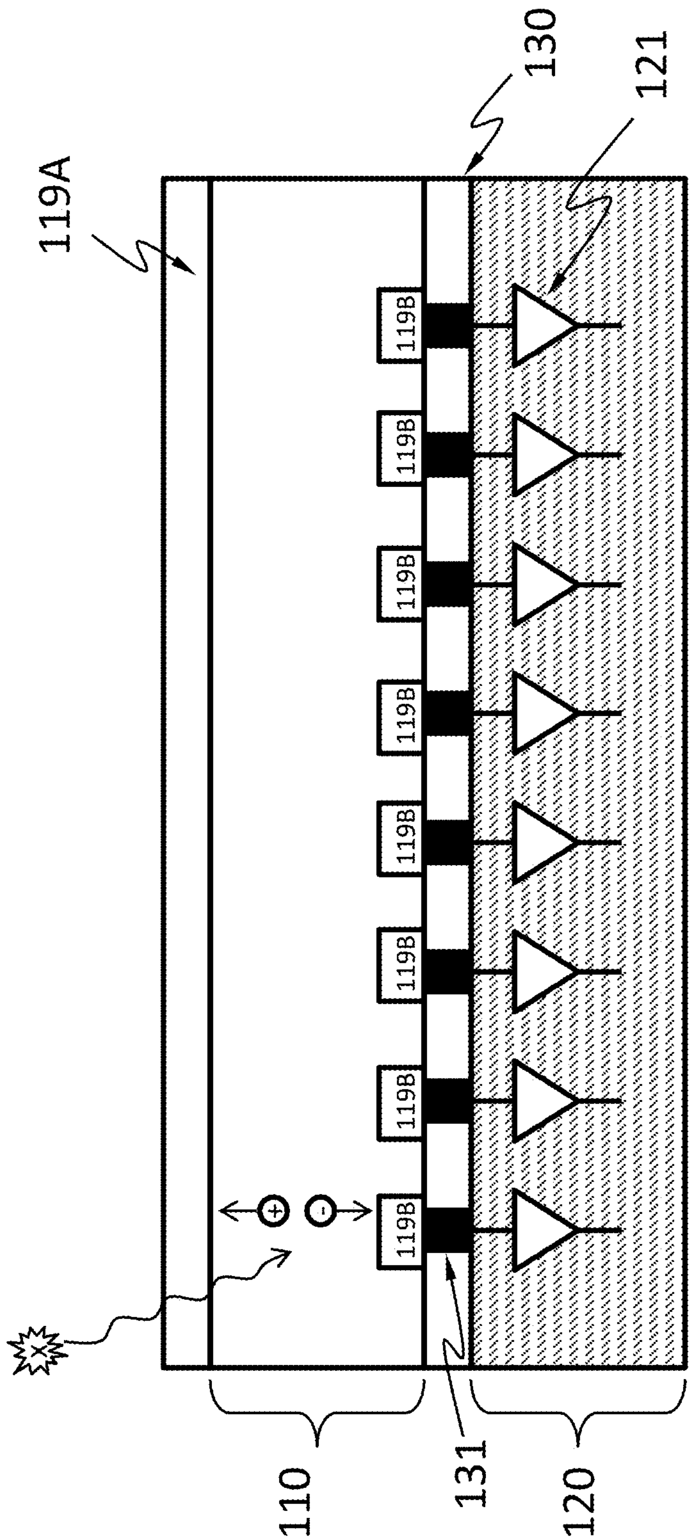


Fig. 1C

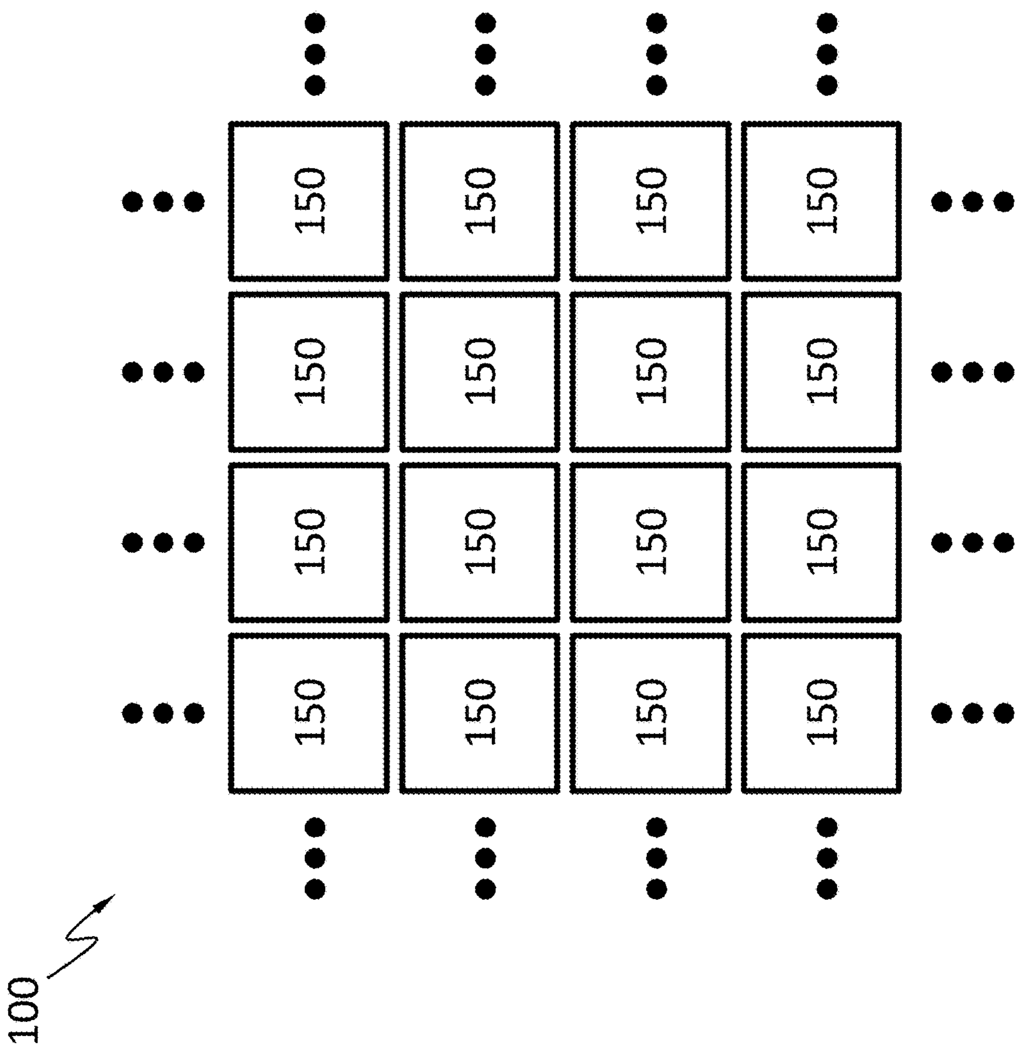

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Fig. 2

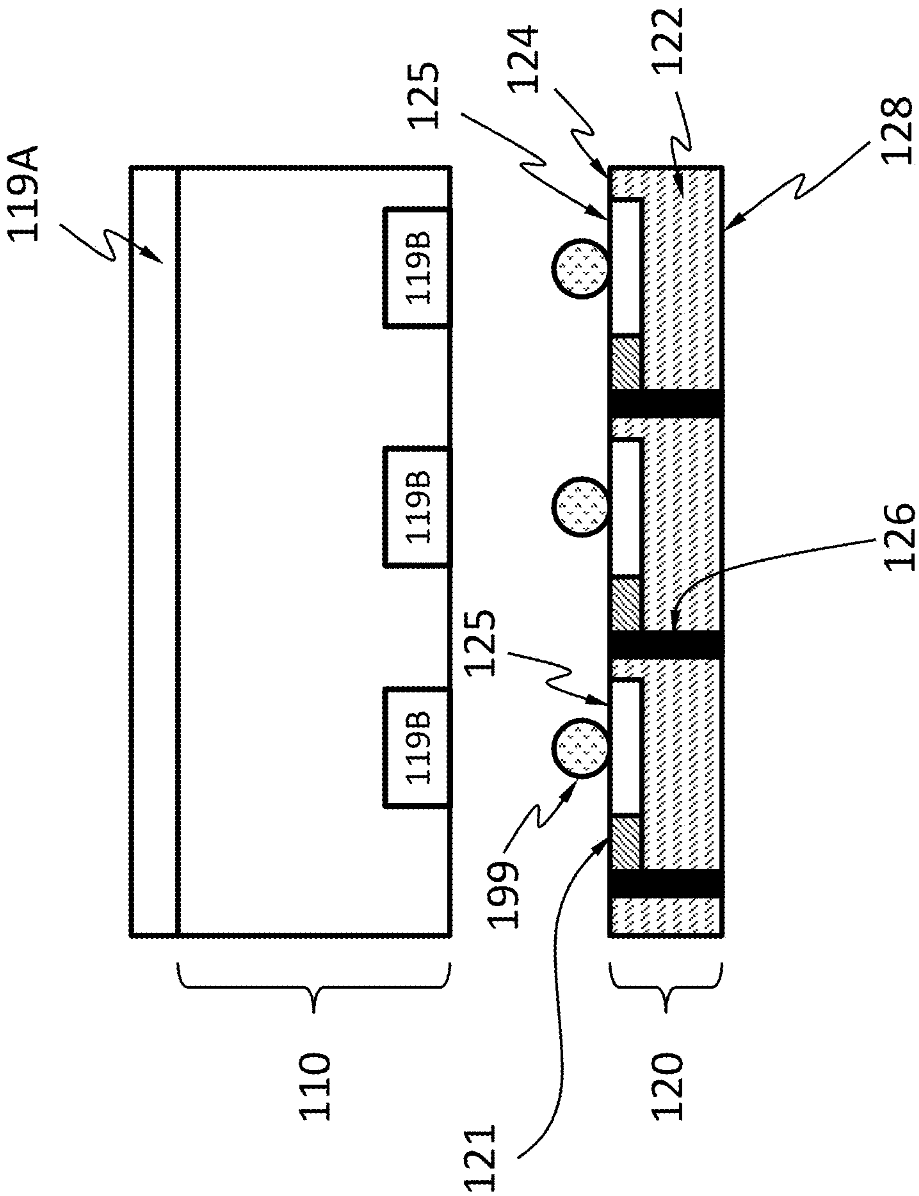


Fig. 3

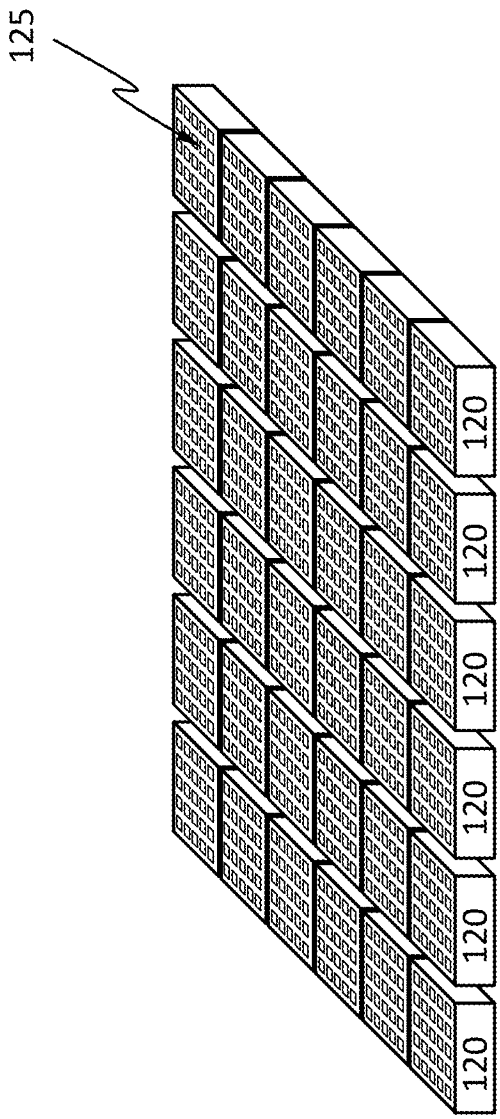


Fig. 4A

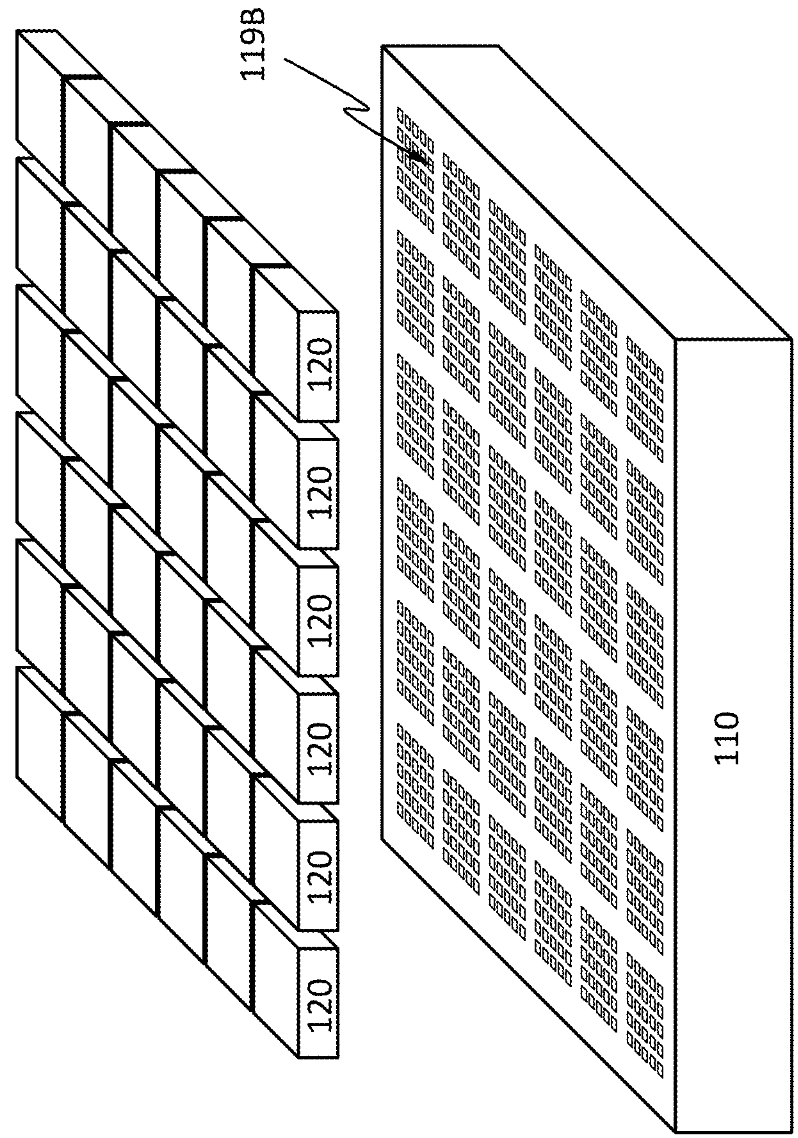


Fig. 4B

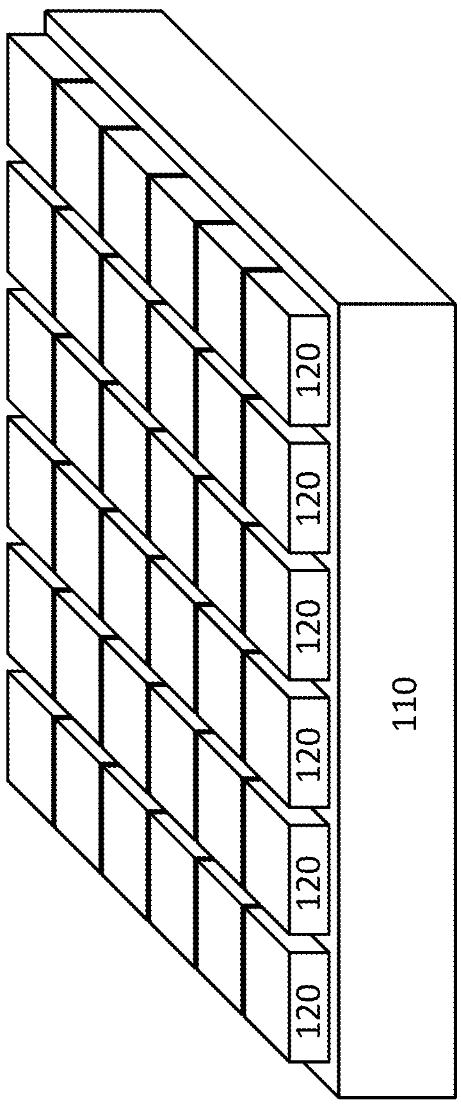


Fig. 4C

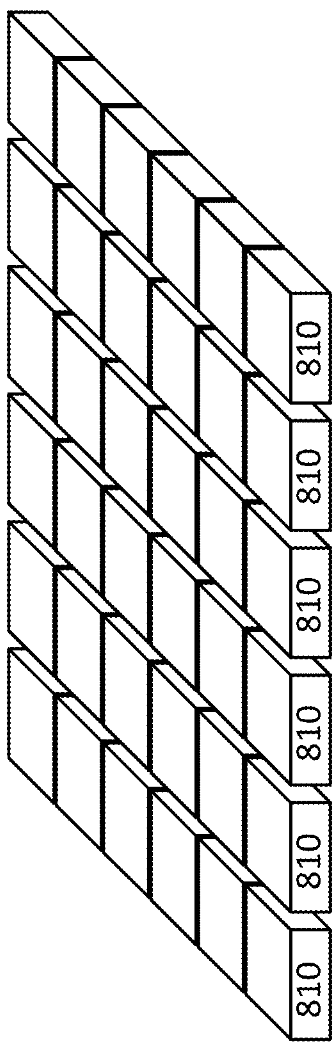


Fig. 5A

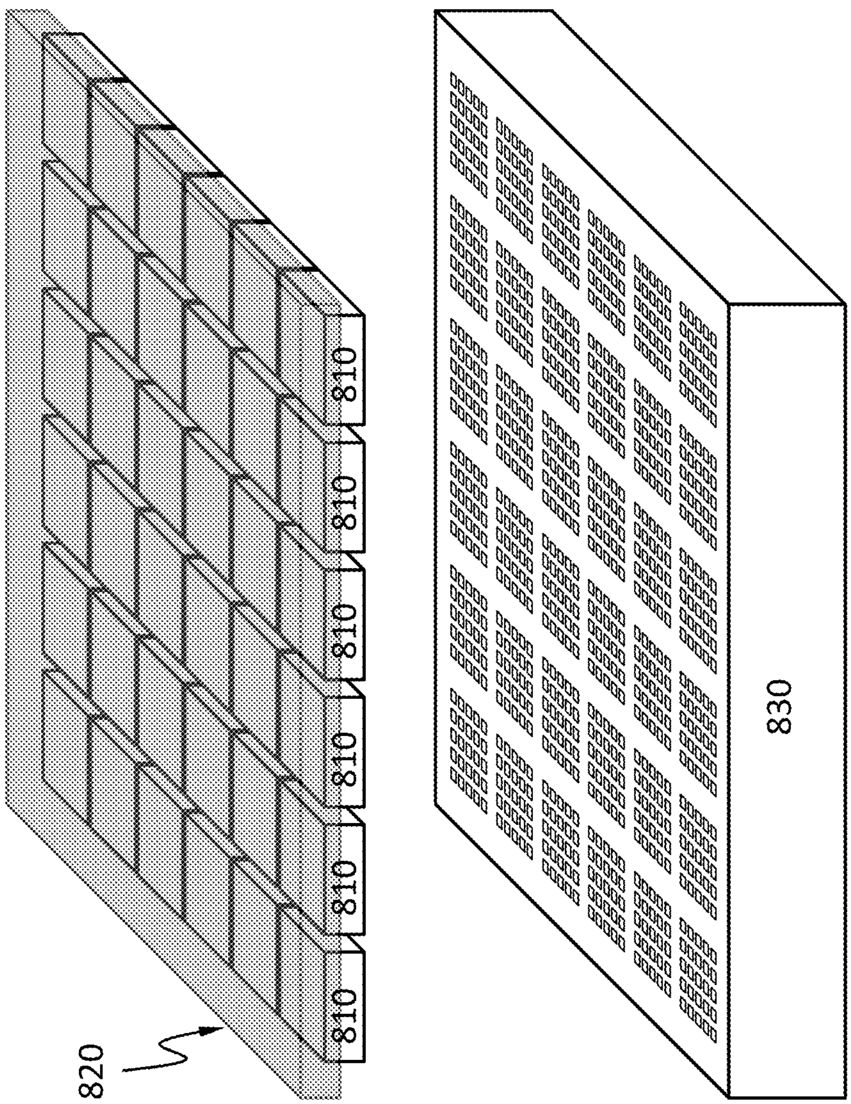


Fig. 5B

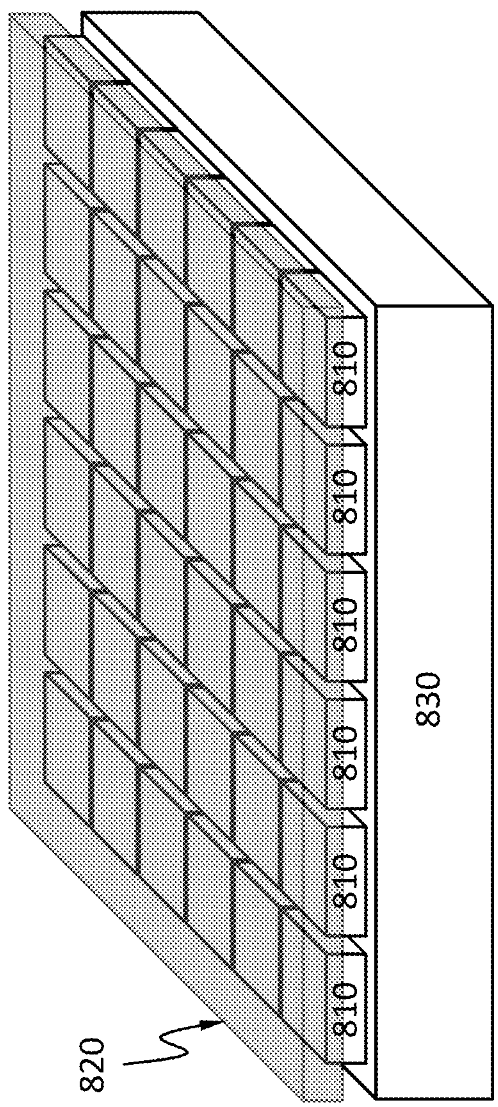


Fig. 5C

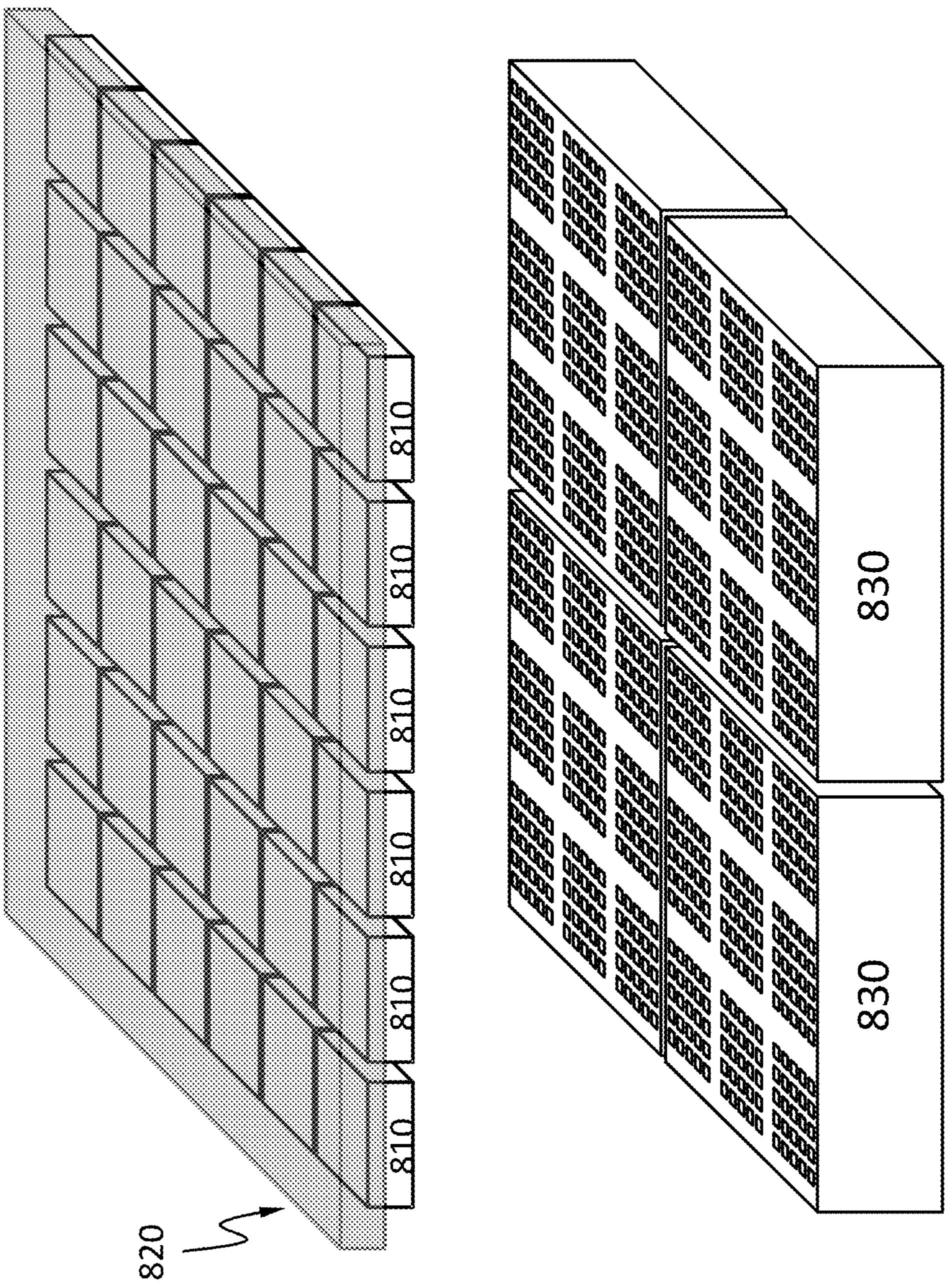


Fig. 5D

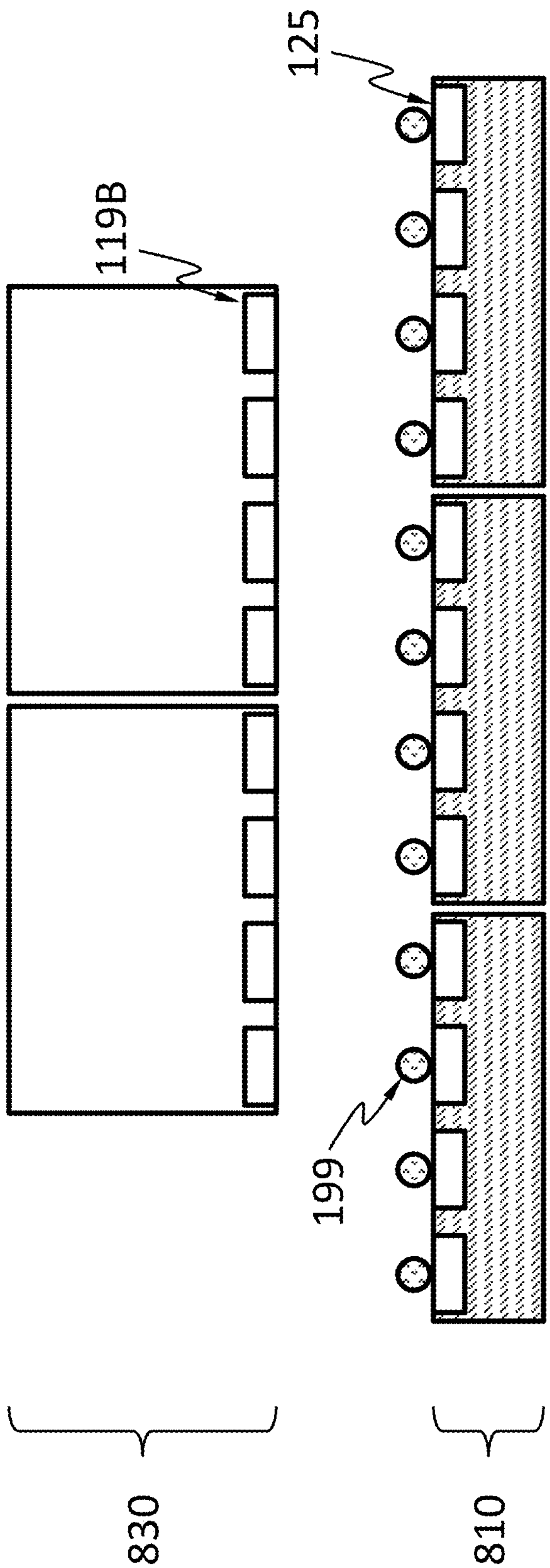
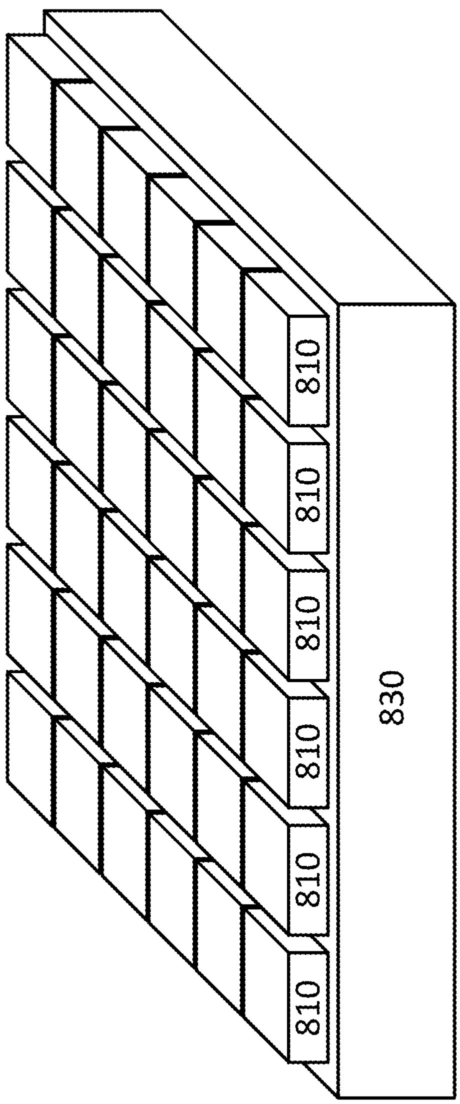


Fig. 5E



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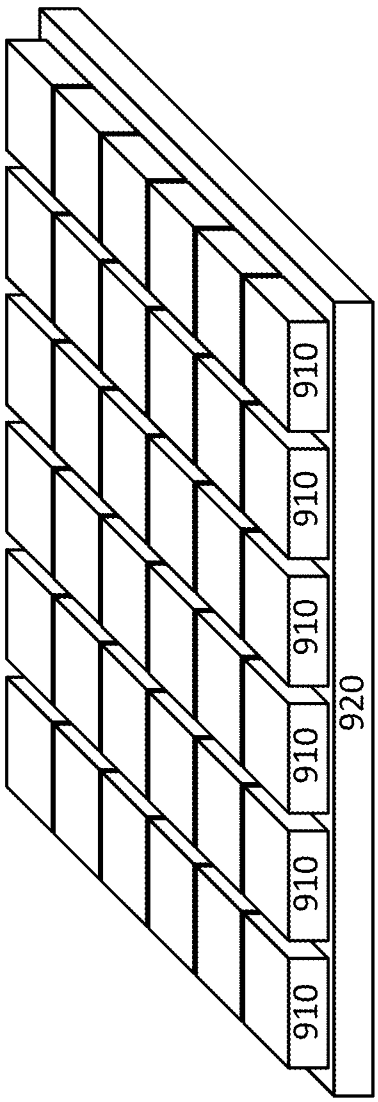

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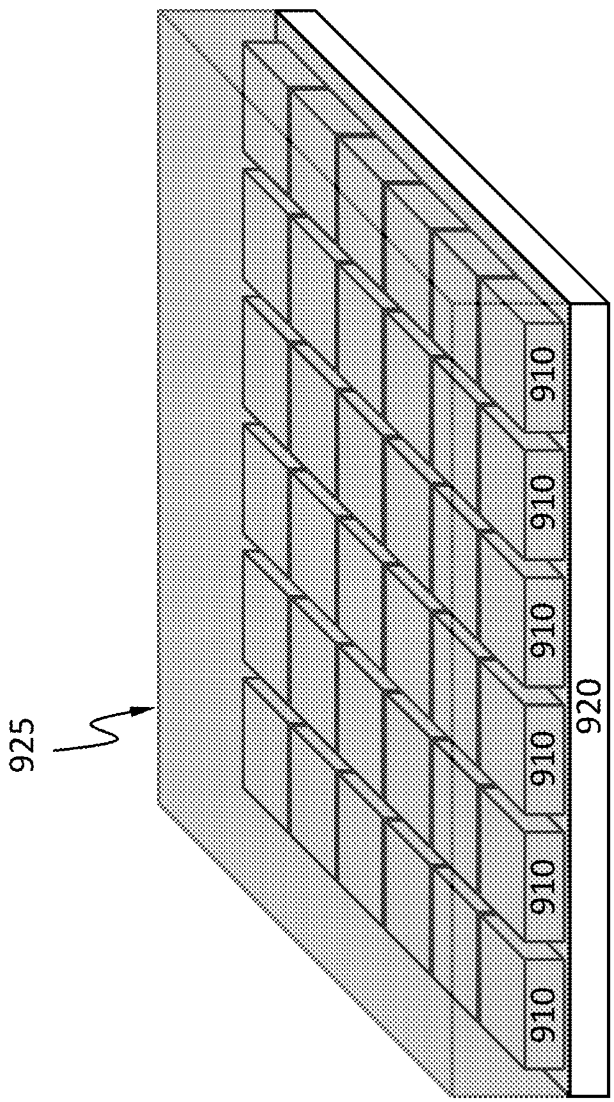

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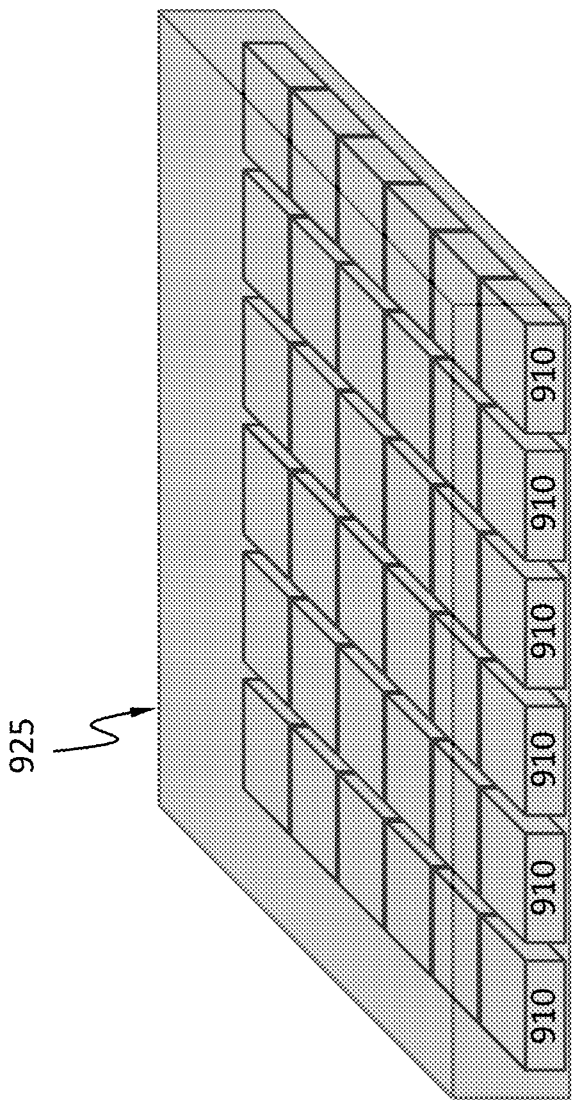

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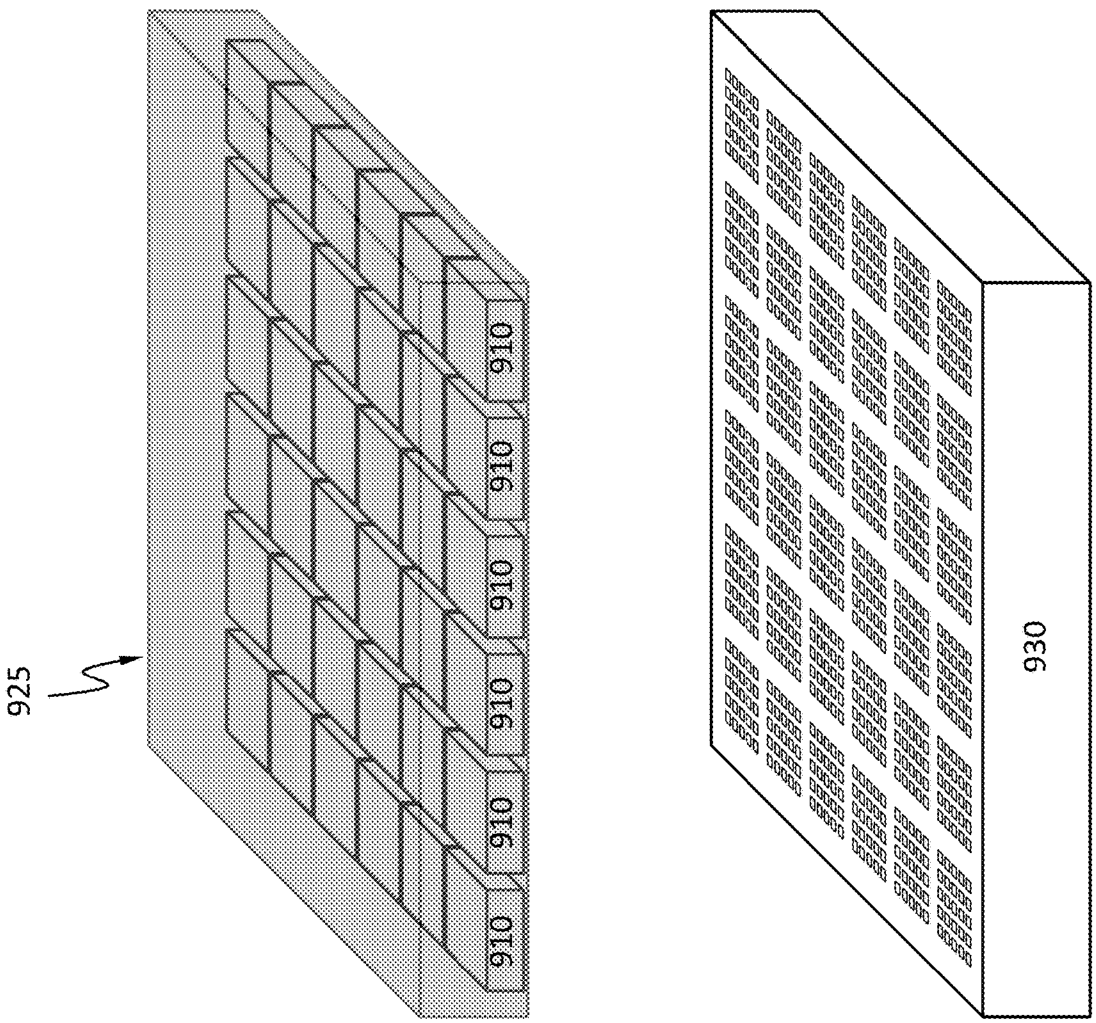


Fig. 6D

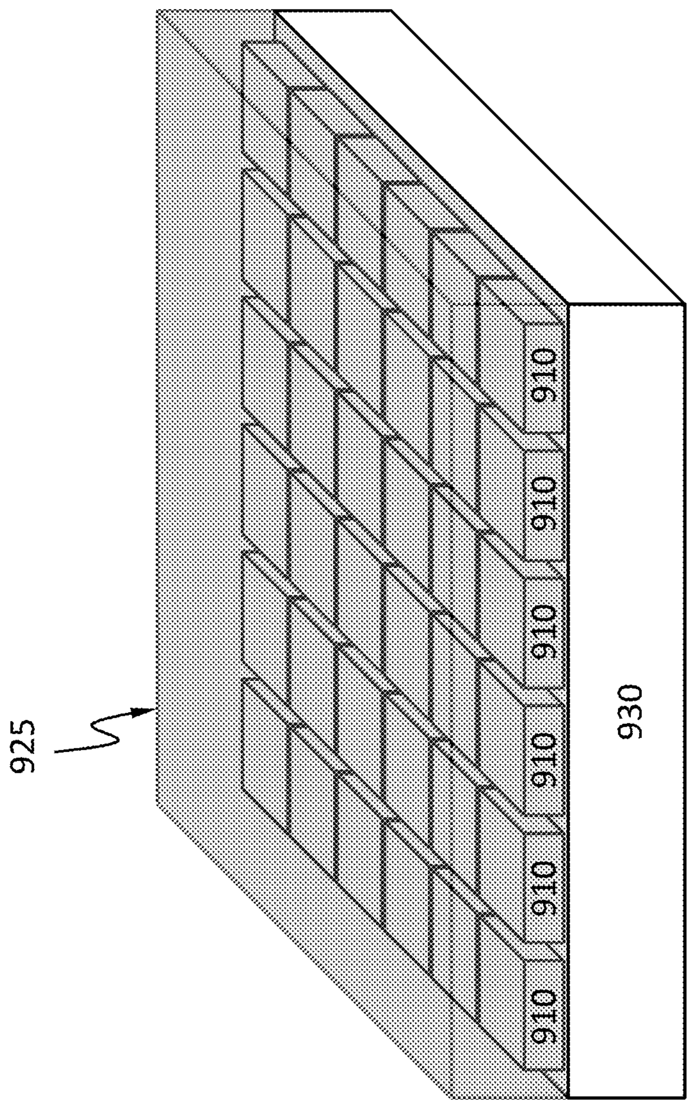
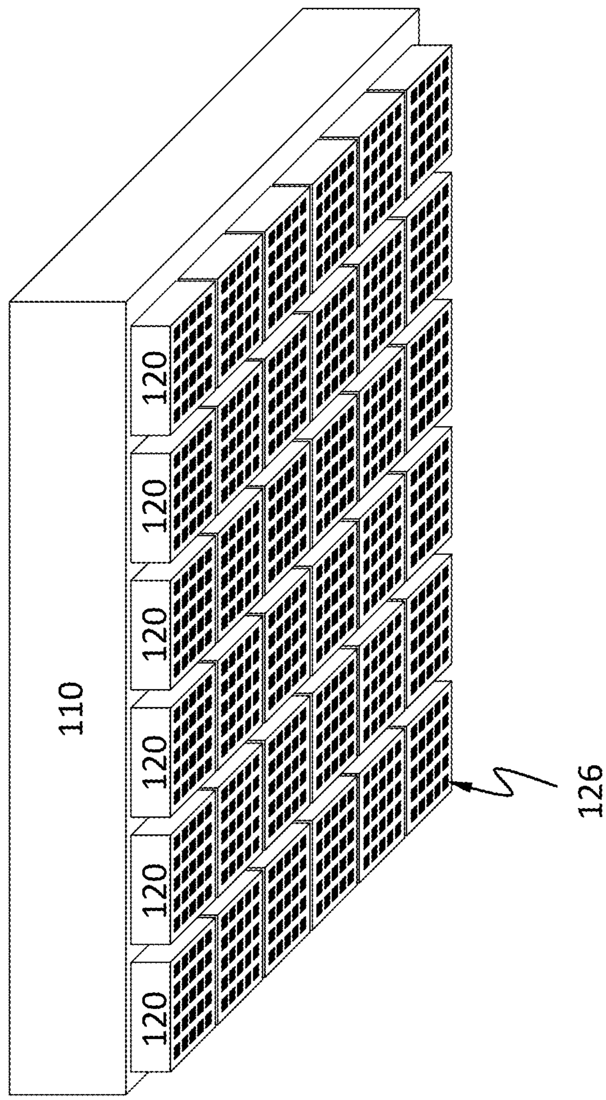


Fig. 6E



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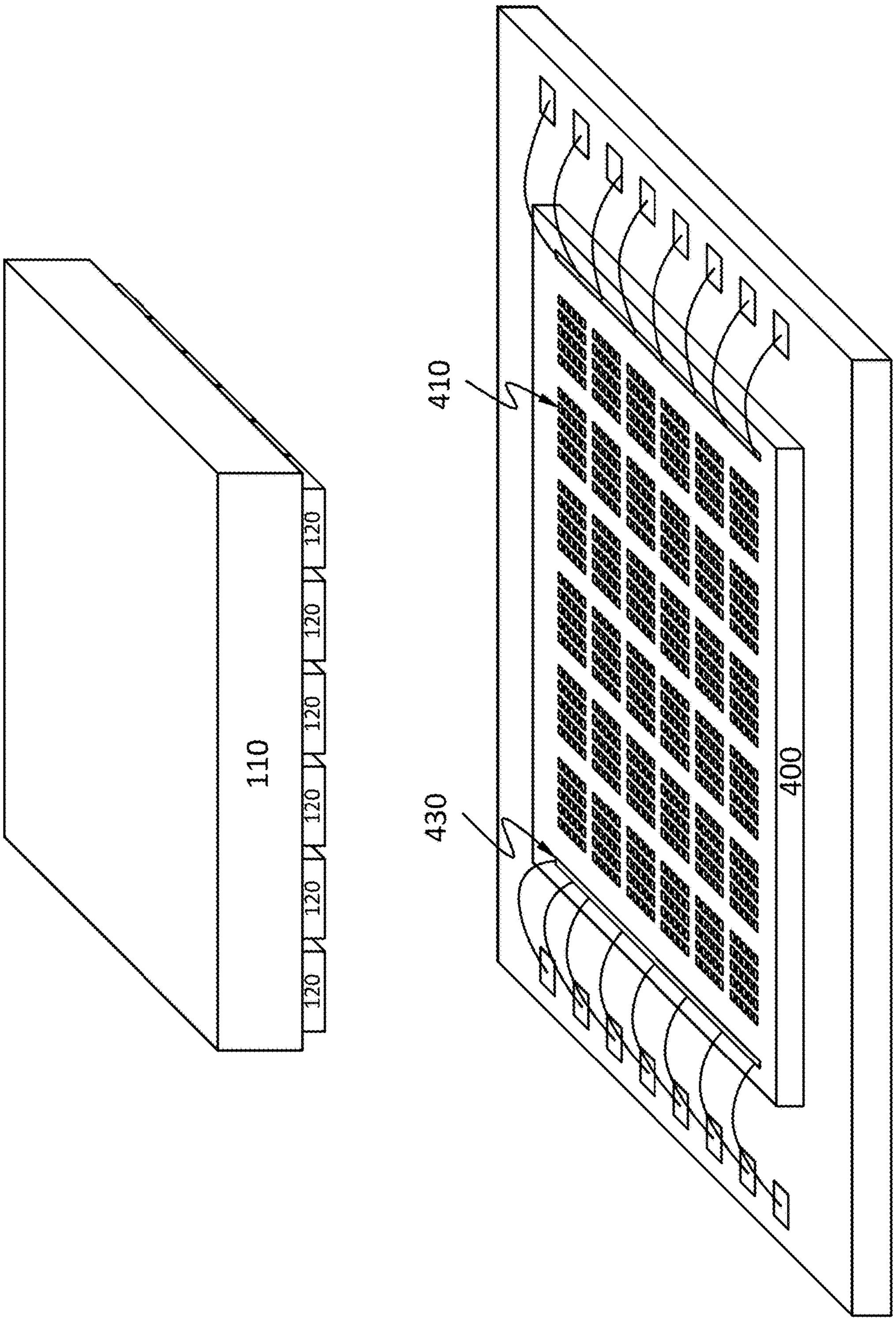

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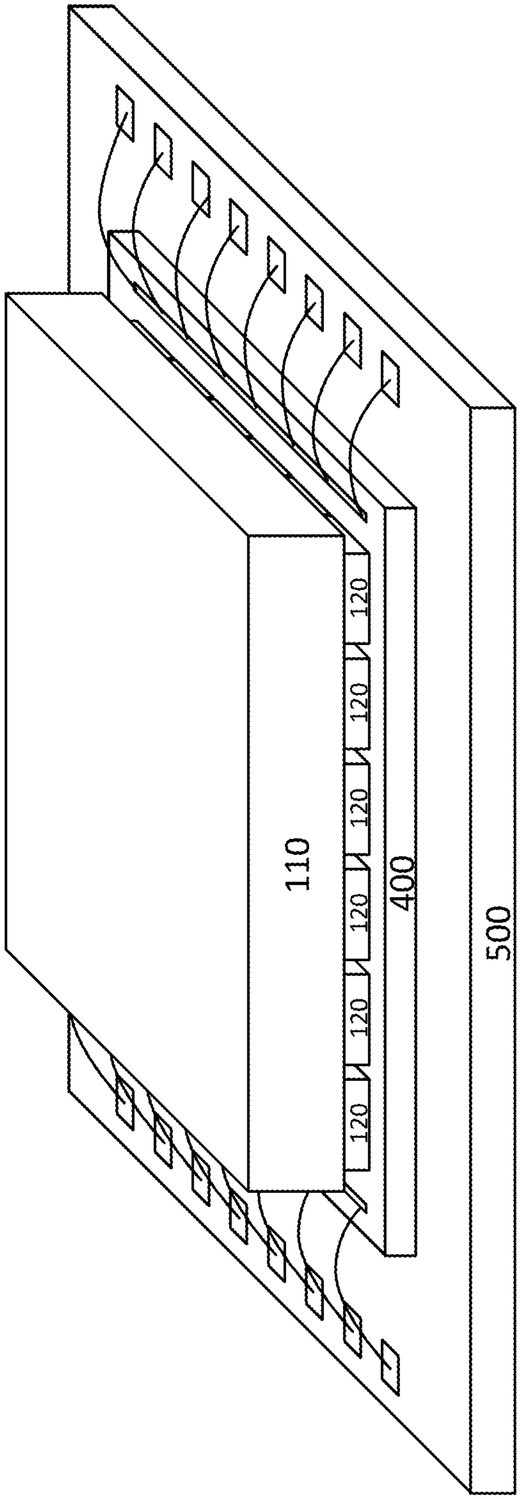


Fig. 7C

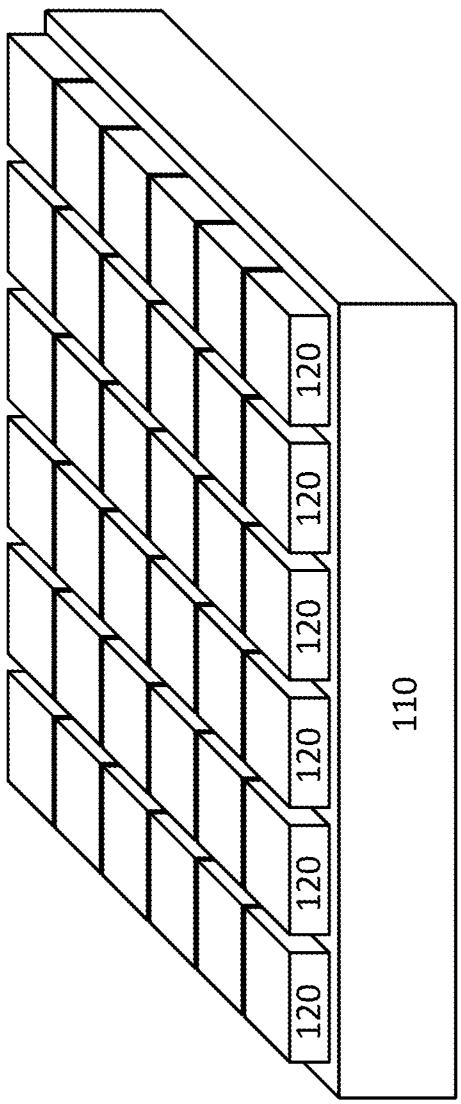
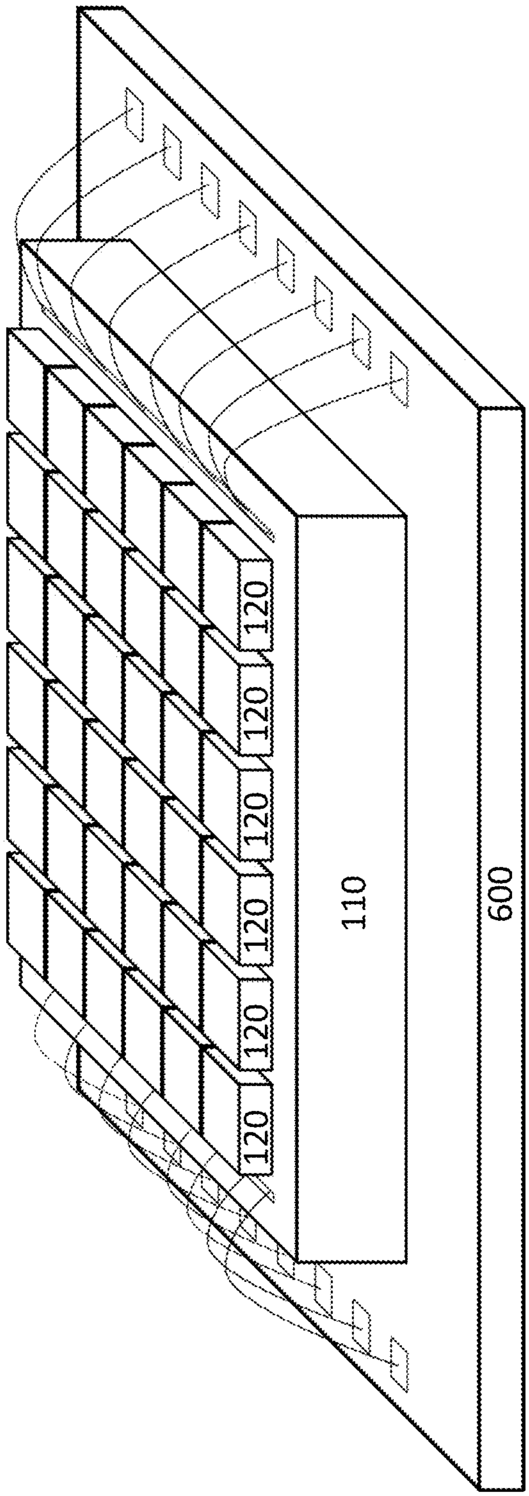


Fig. 8A



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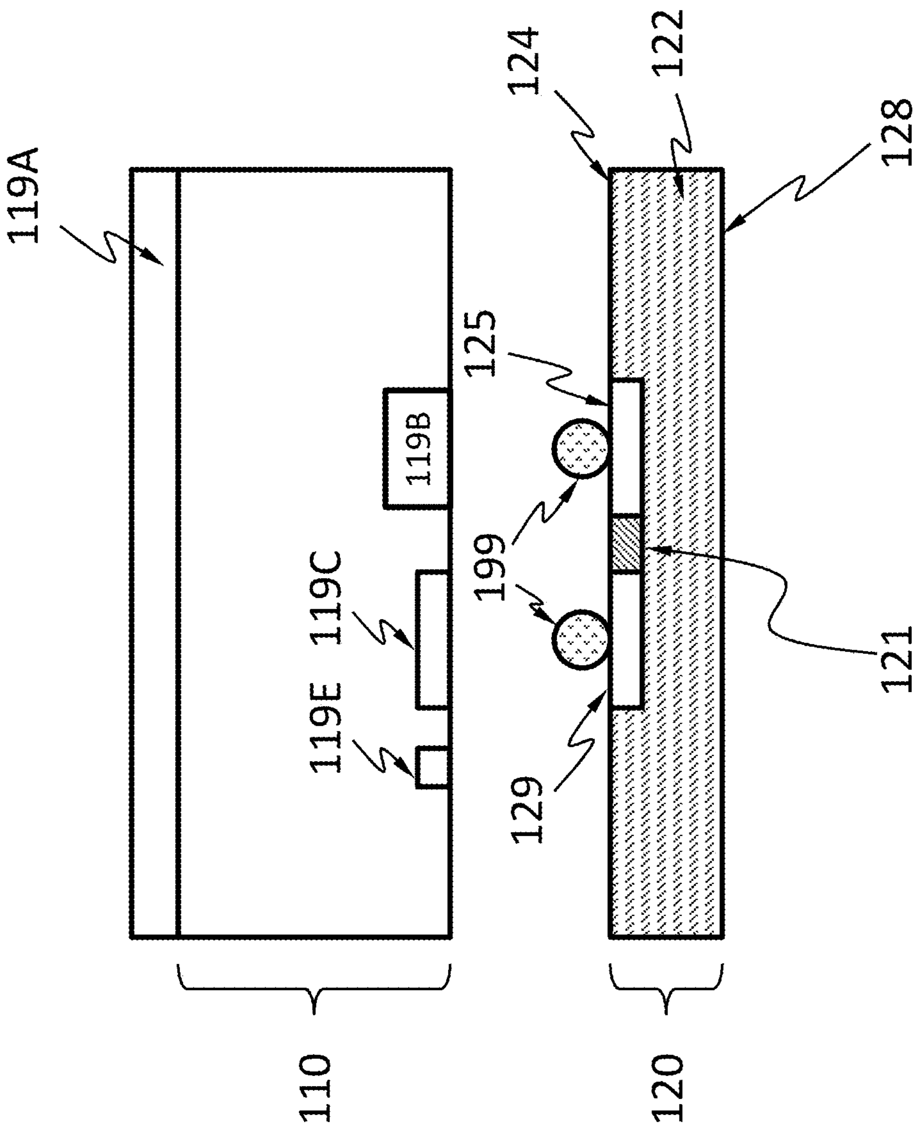

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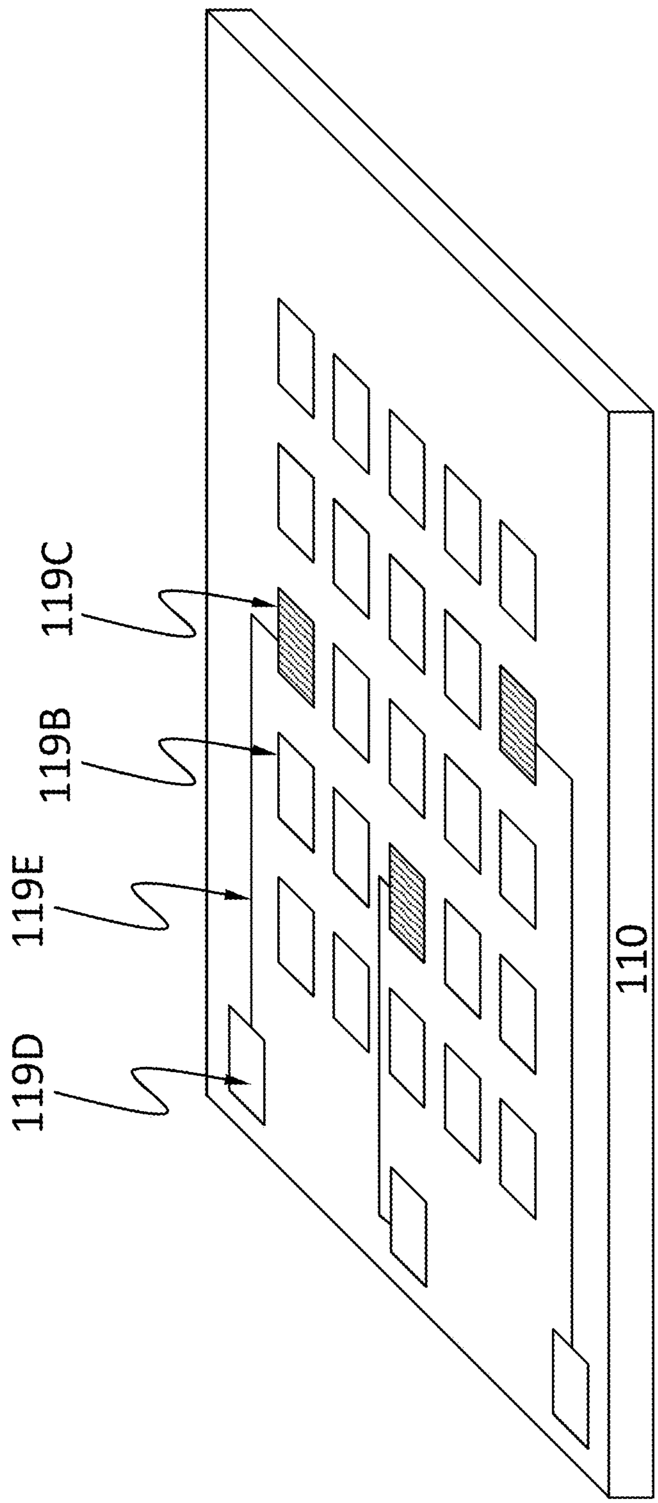

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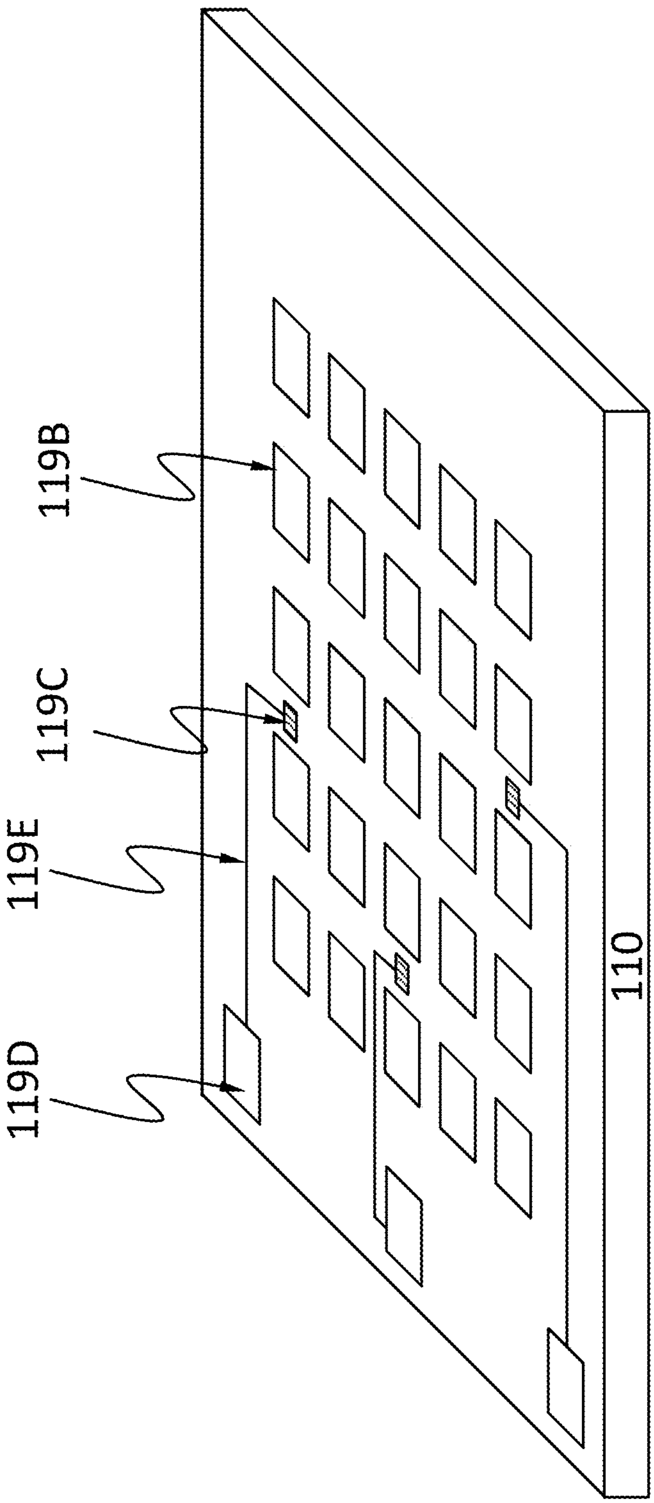

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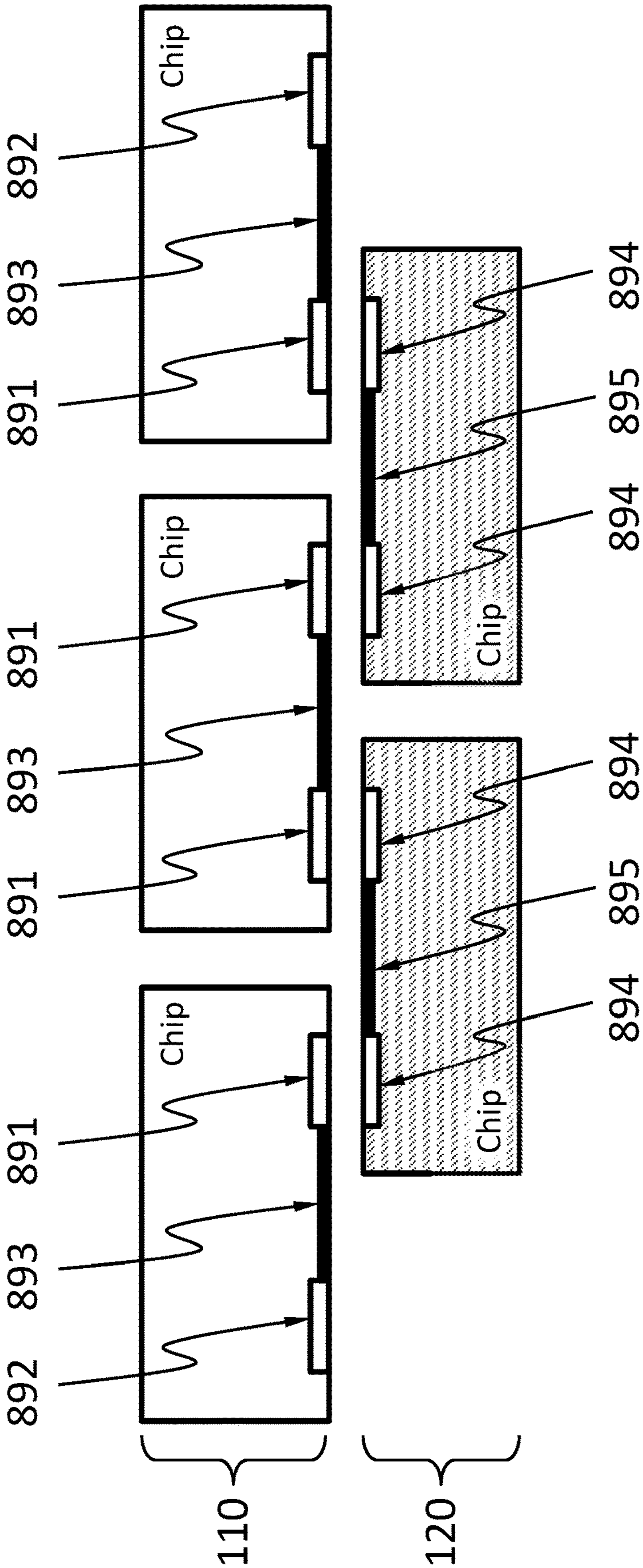

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Fig. 8F

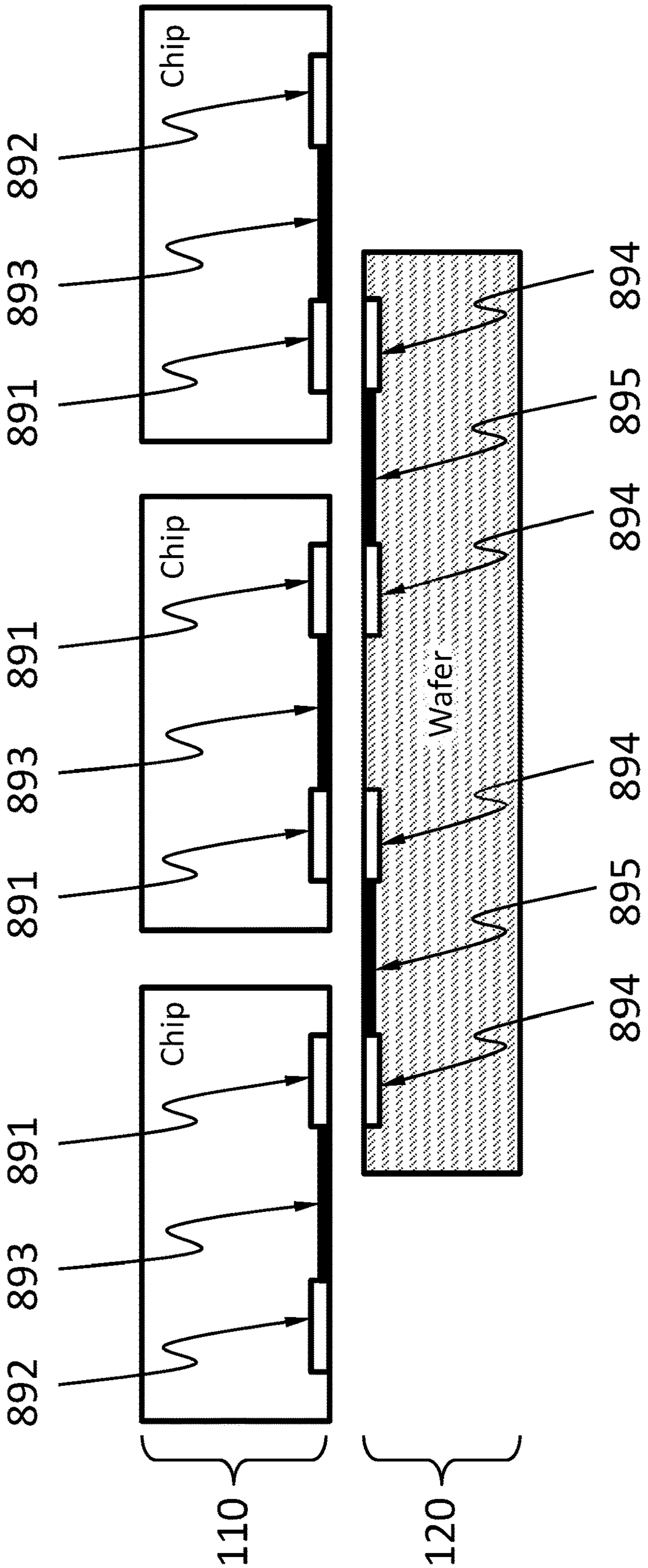
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Fig. 8G

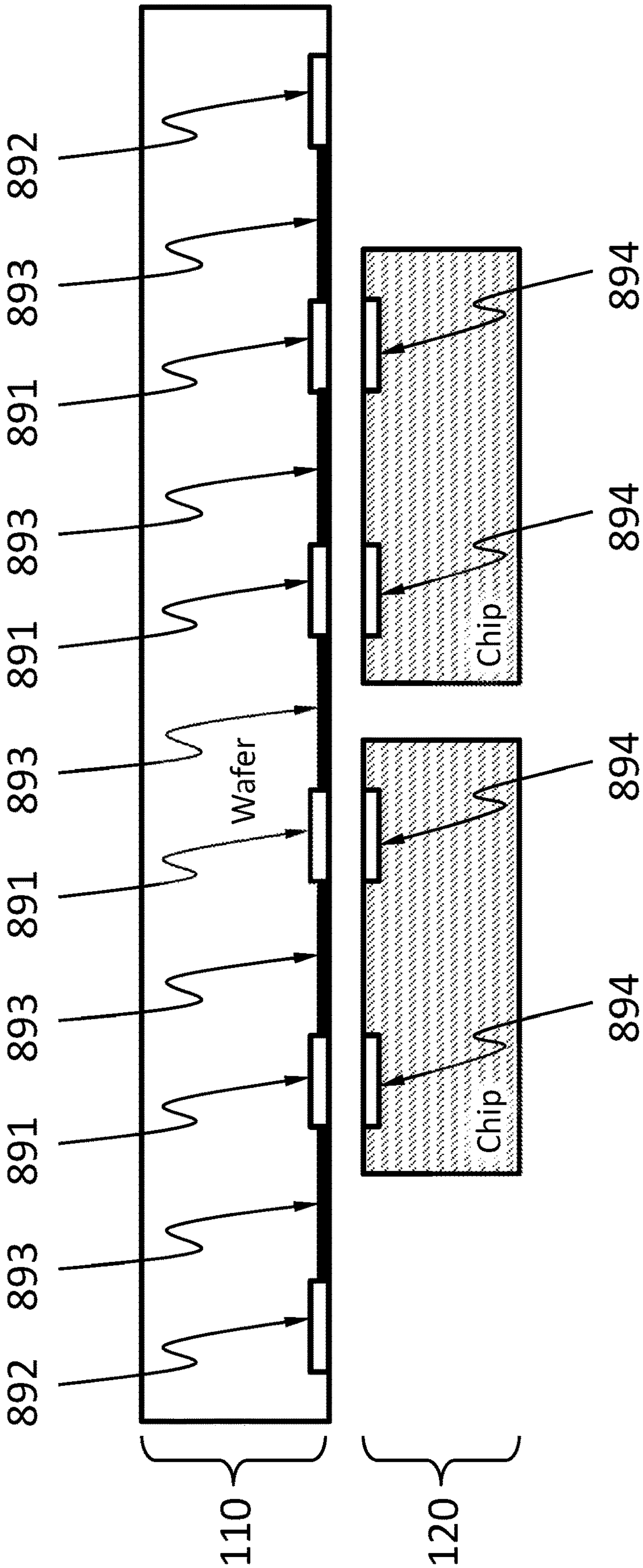
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Fig. 8H

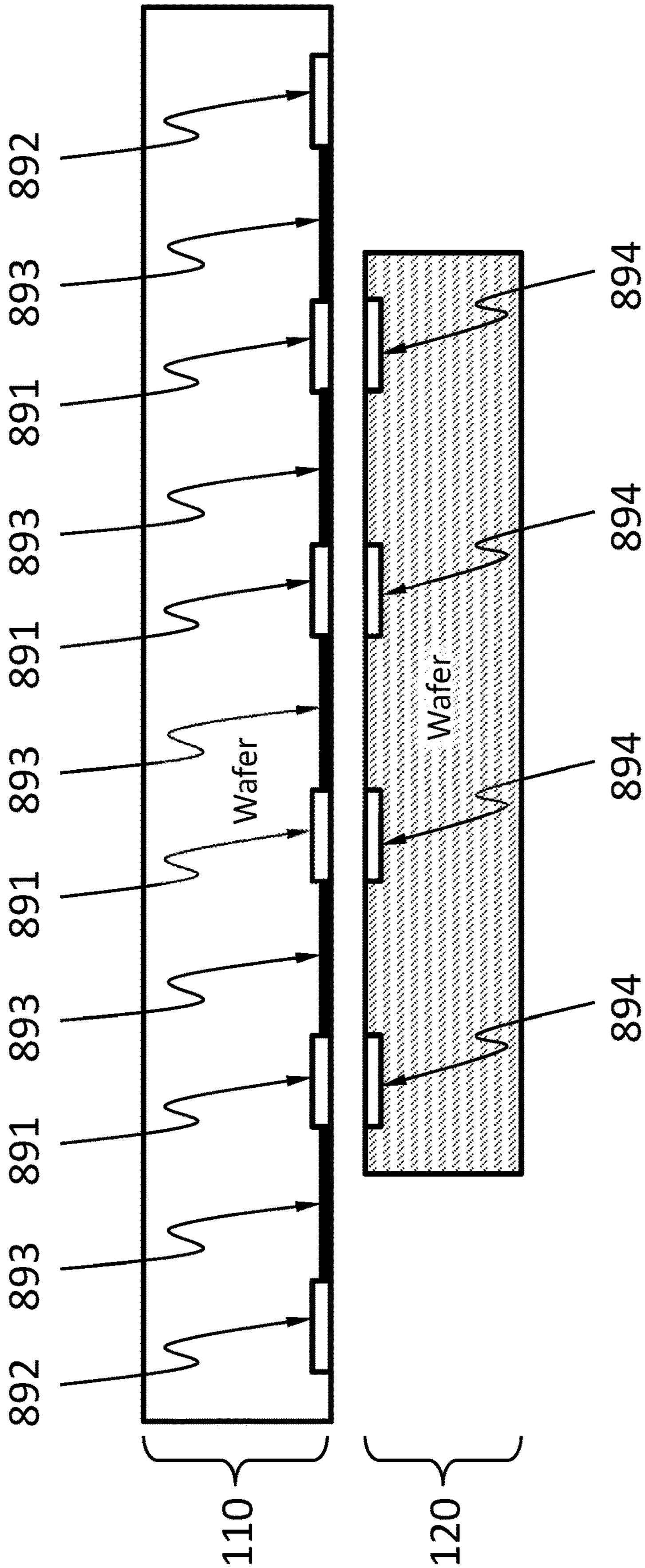
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Fig. 8I

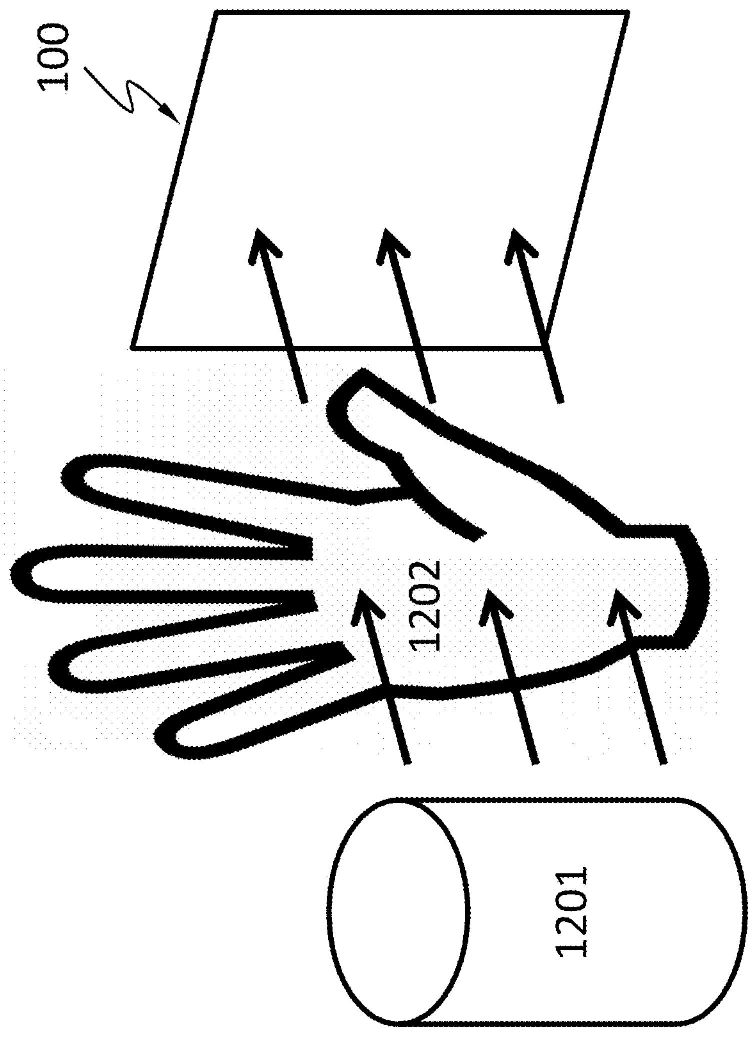
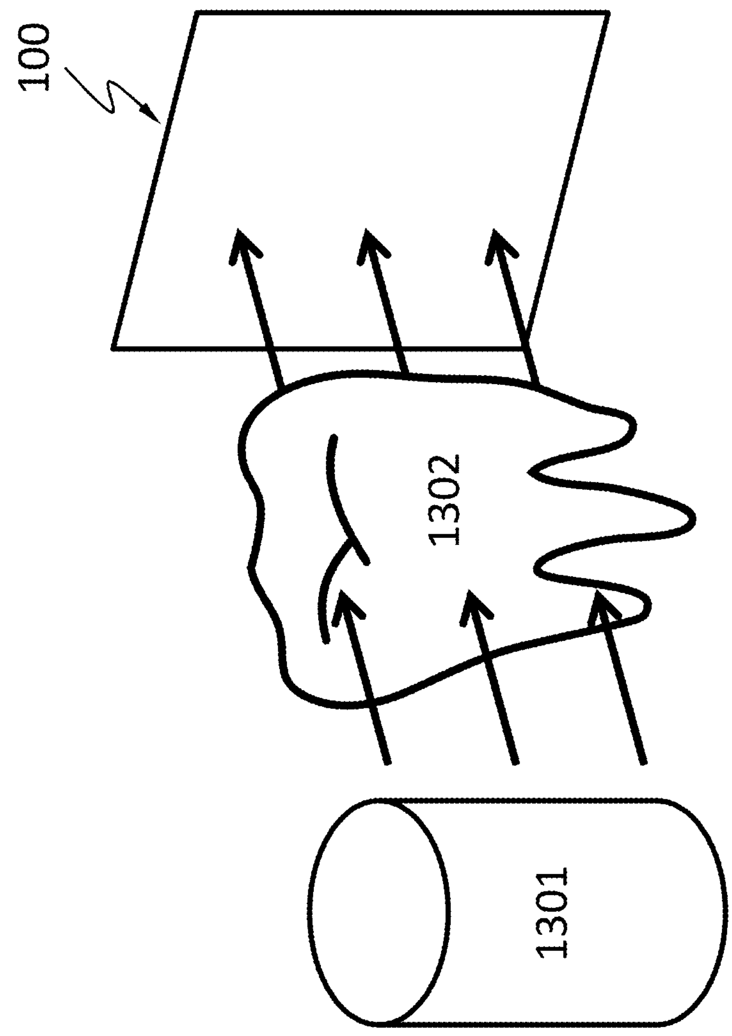


Fig. 9



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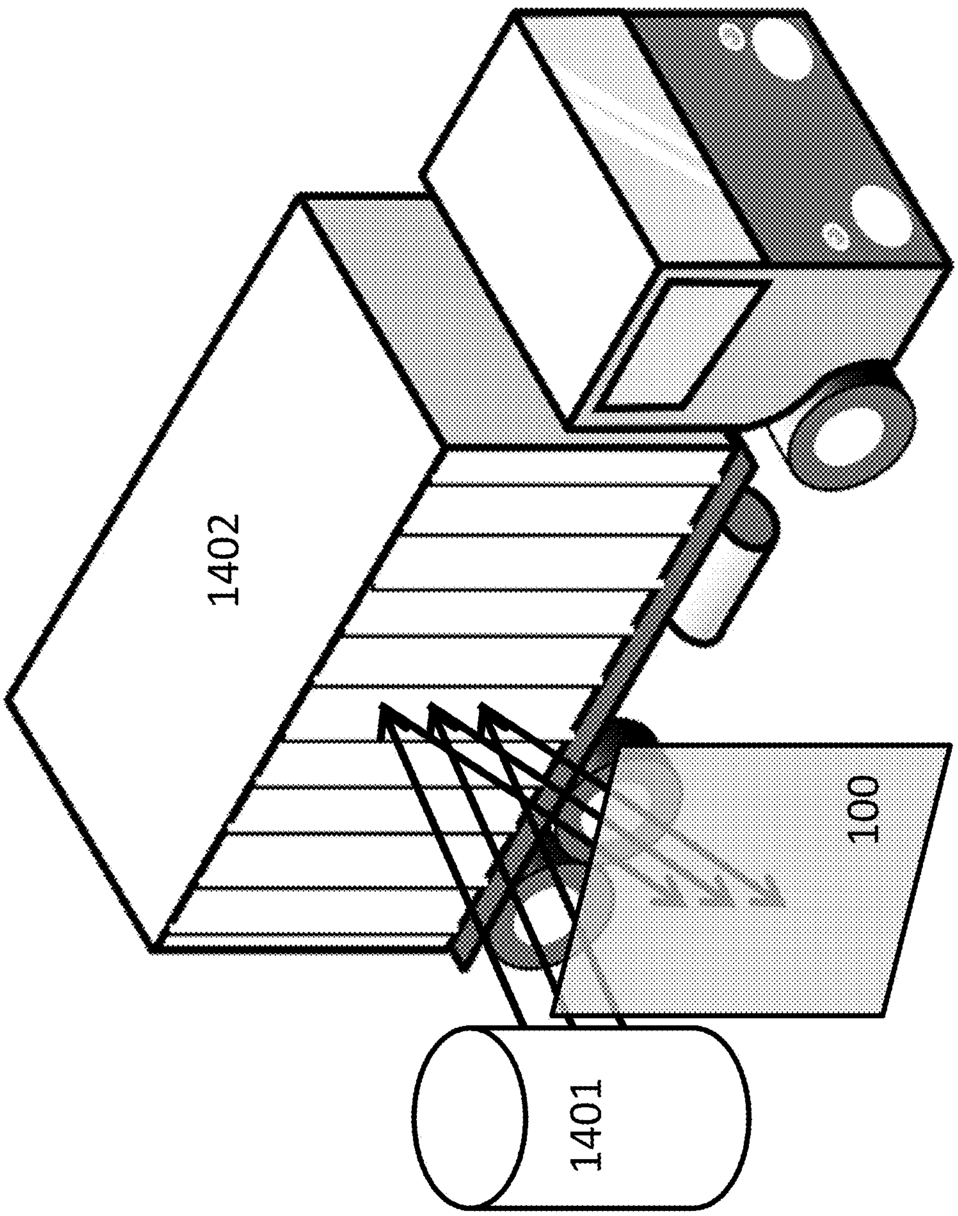


Fig. 11

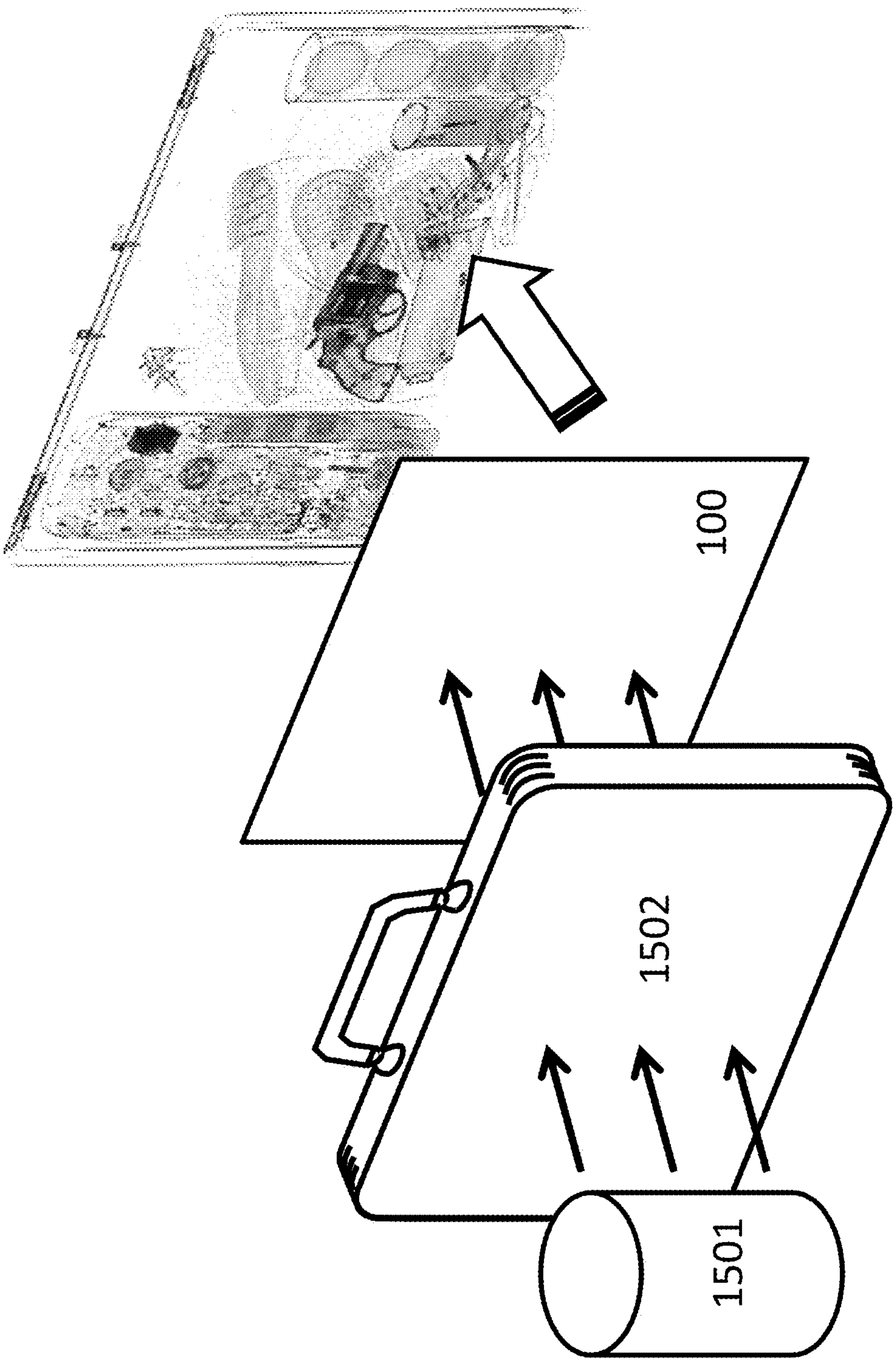
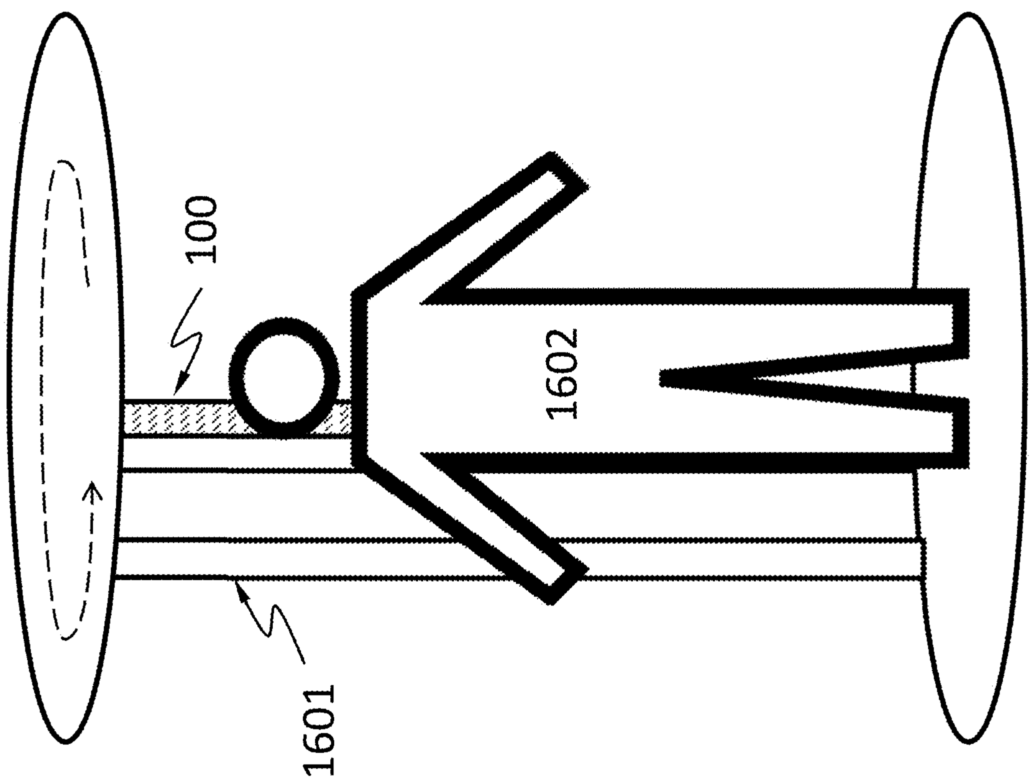


Fig. 12



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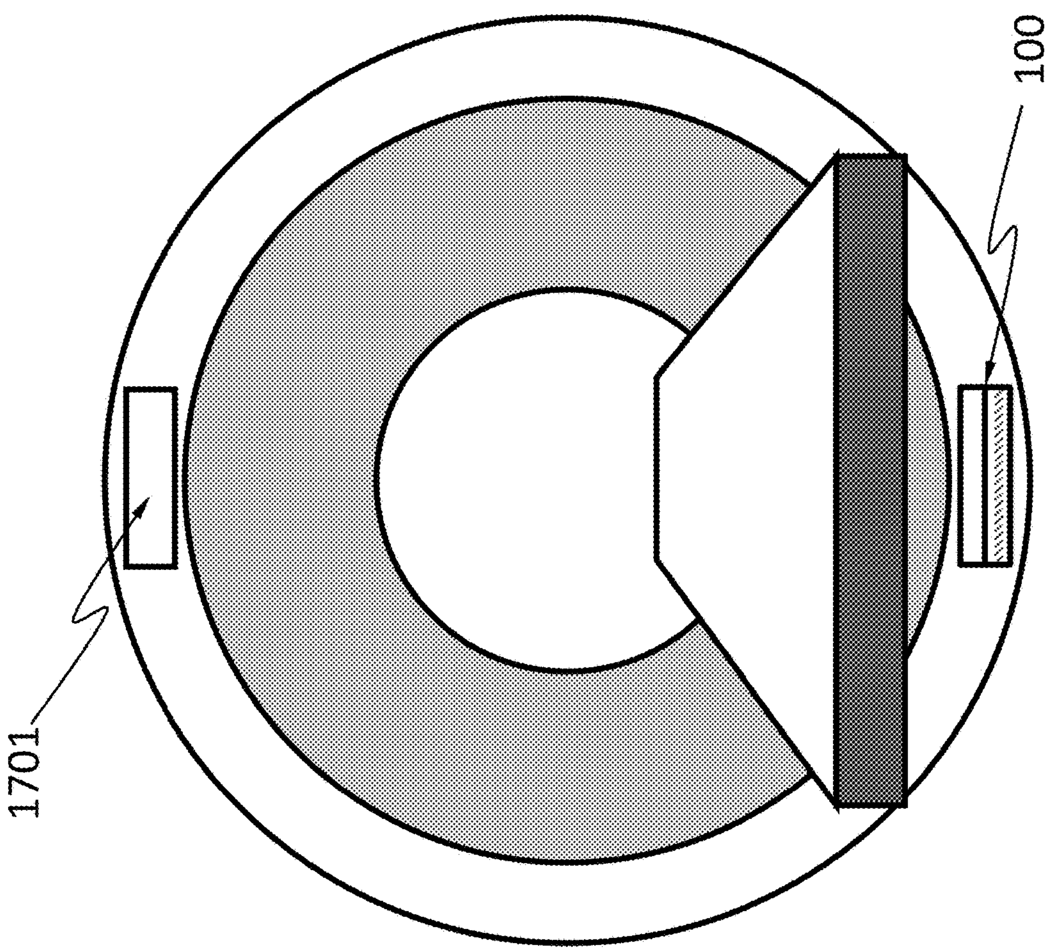

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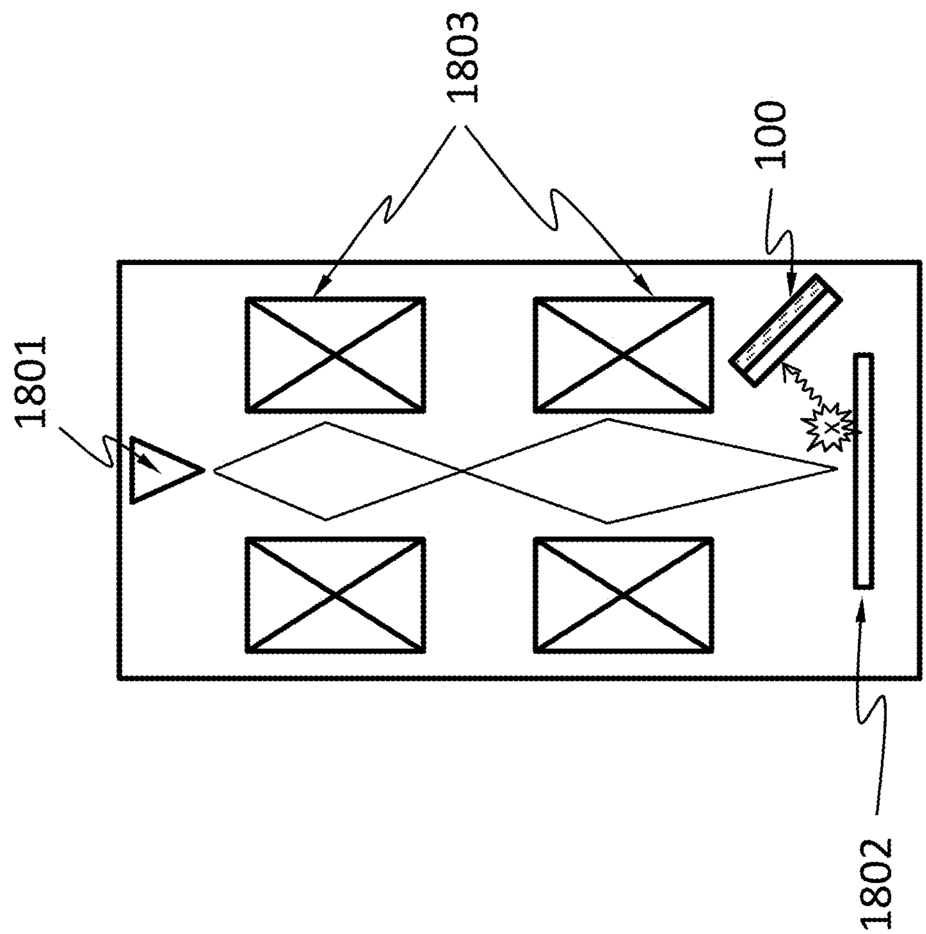

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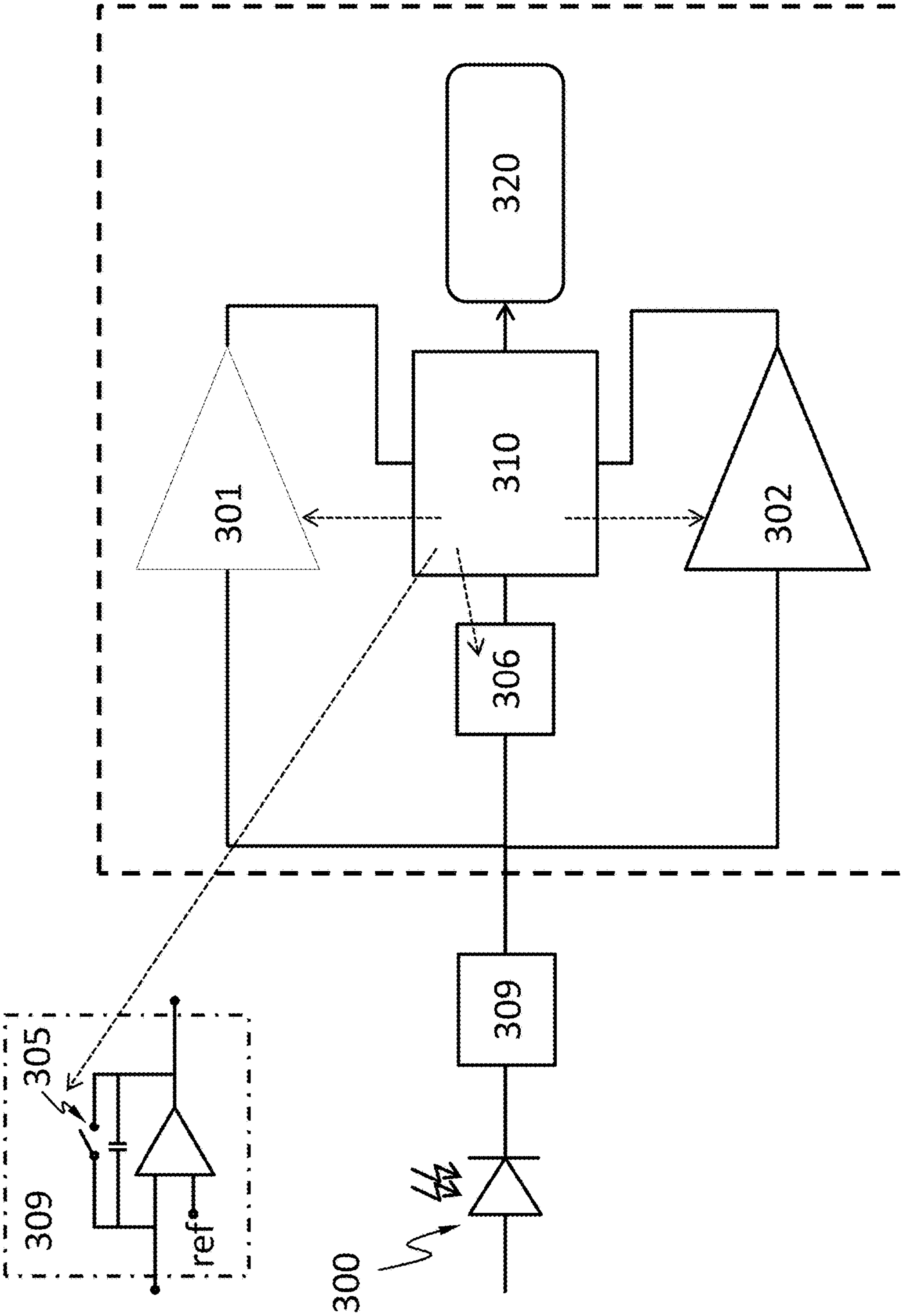


Fig. 16A

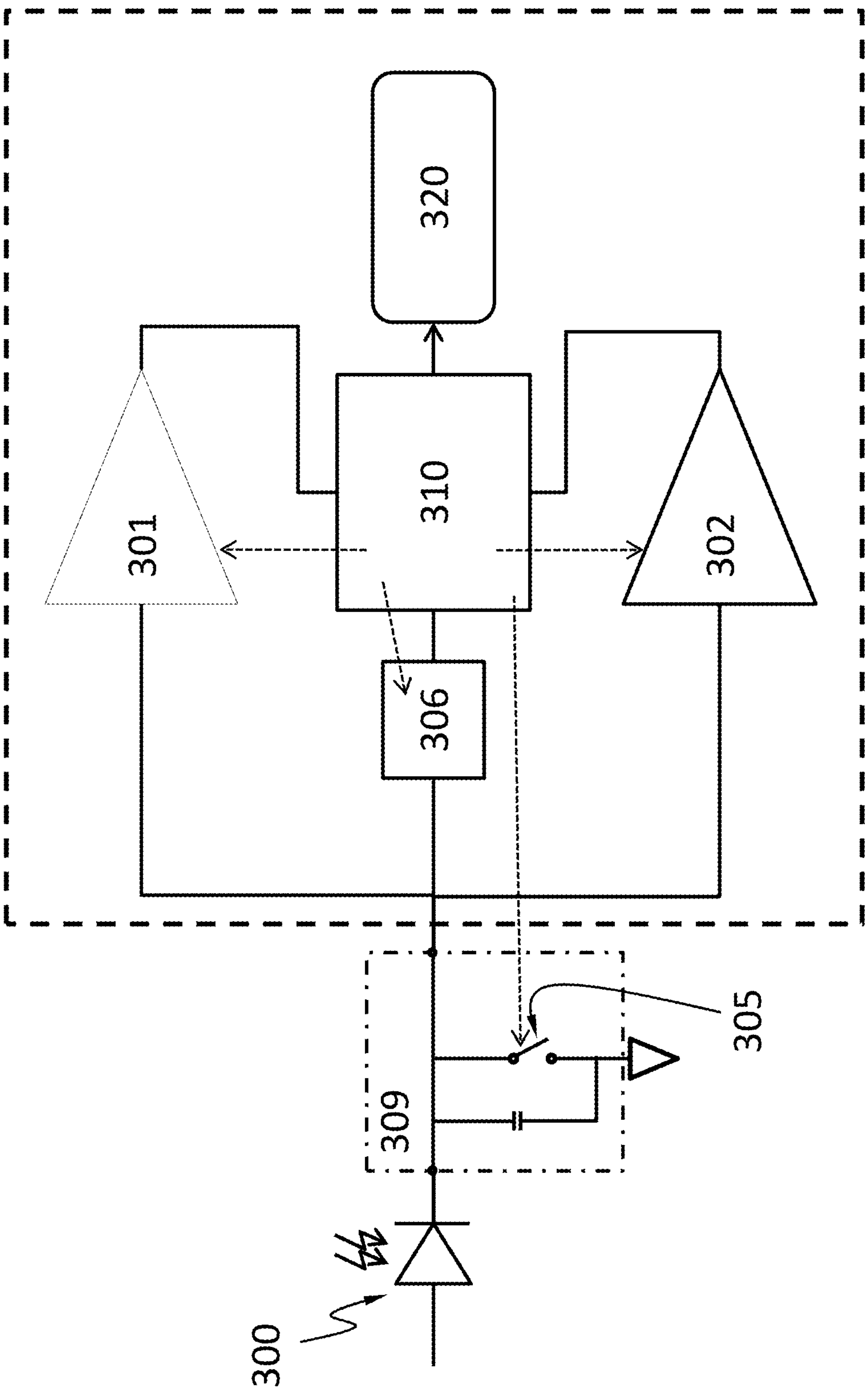
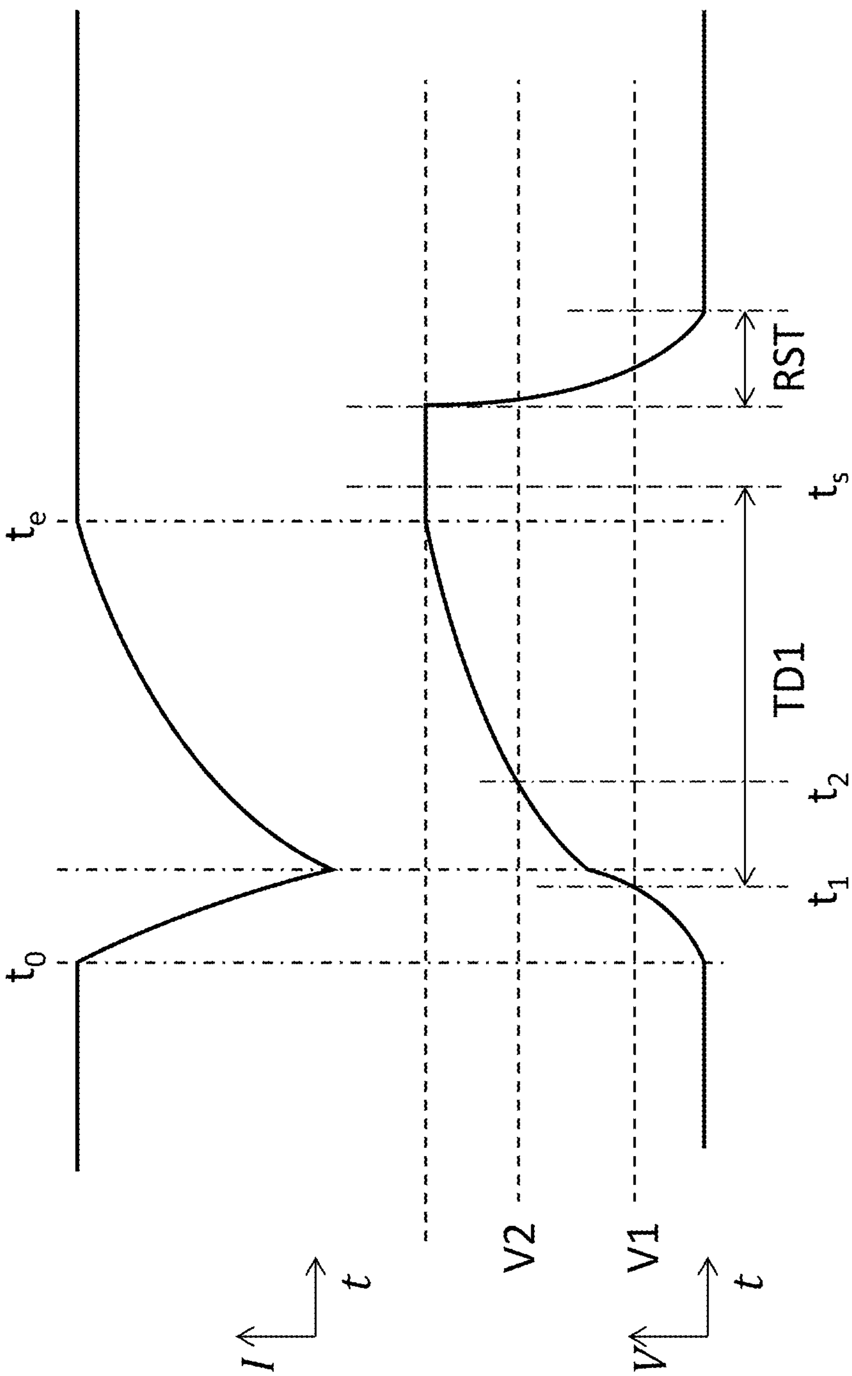


Fig. 16B



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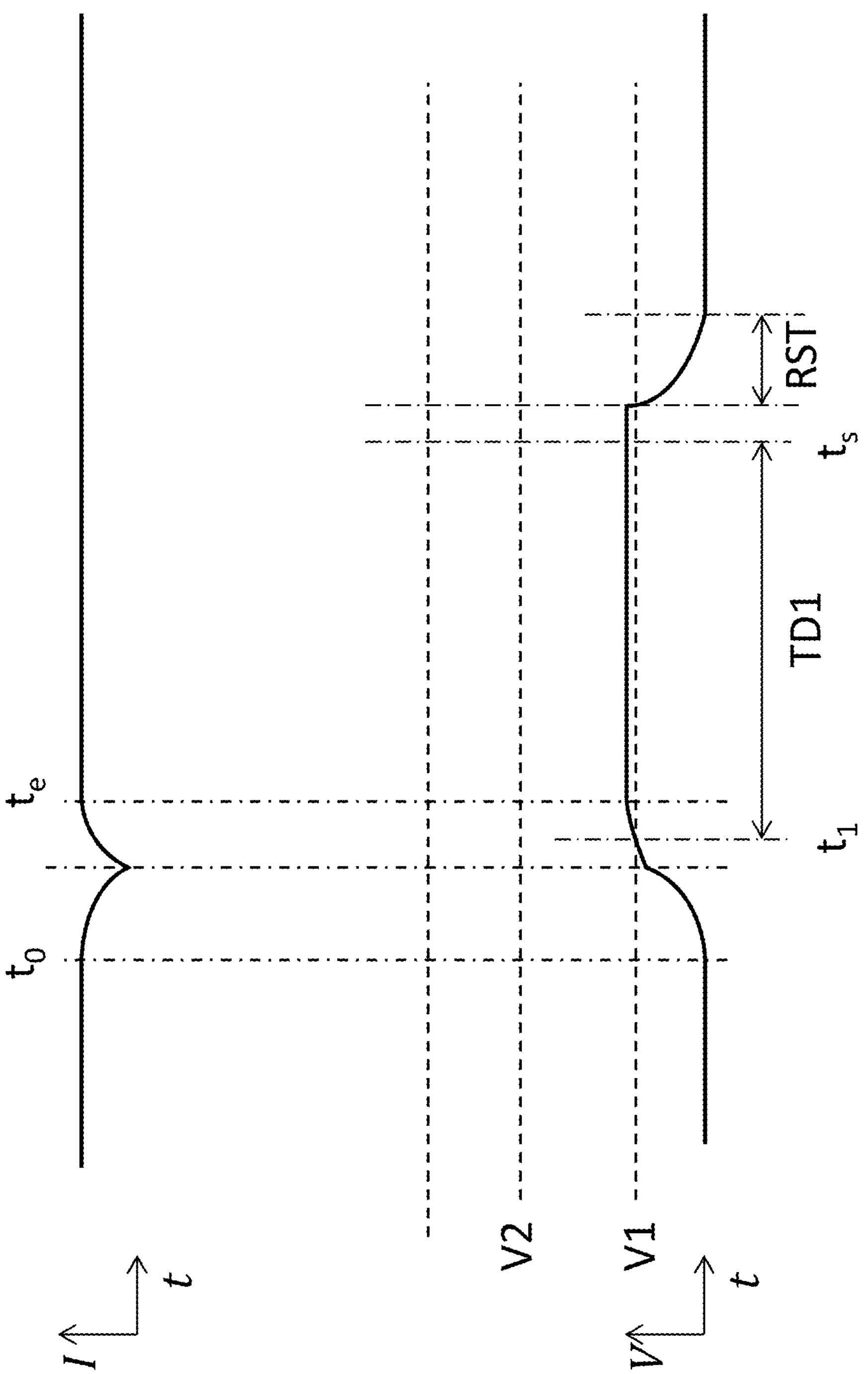
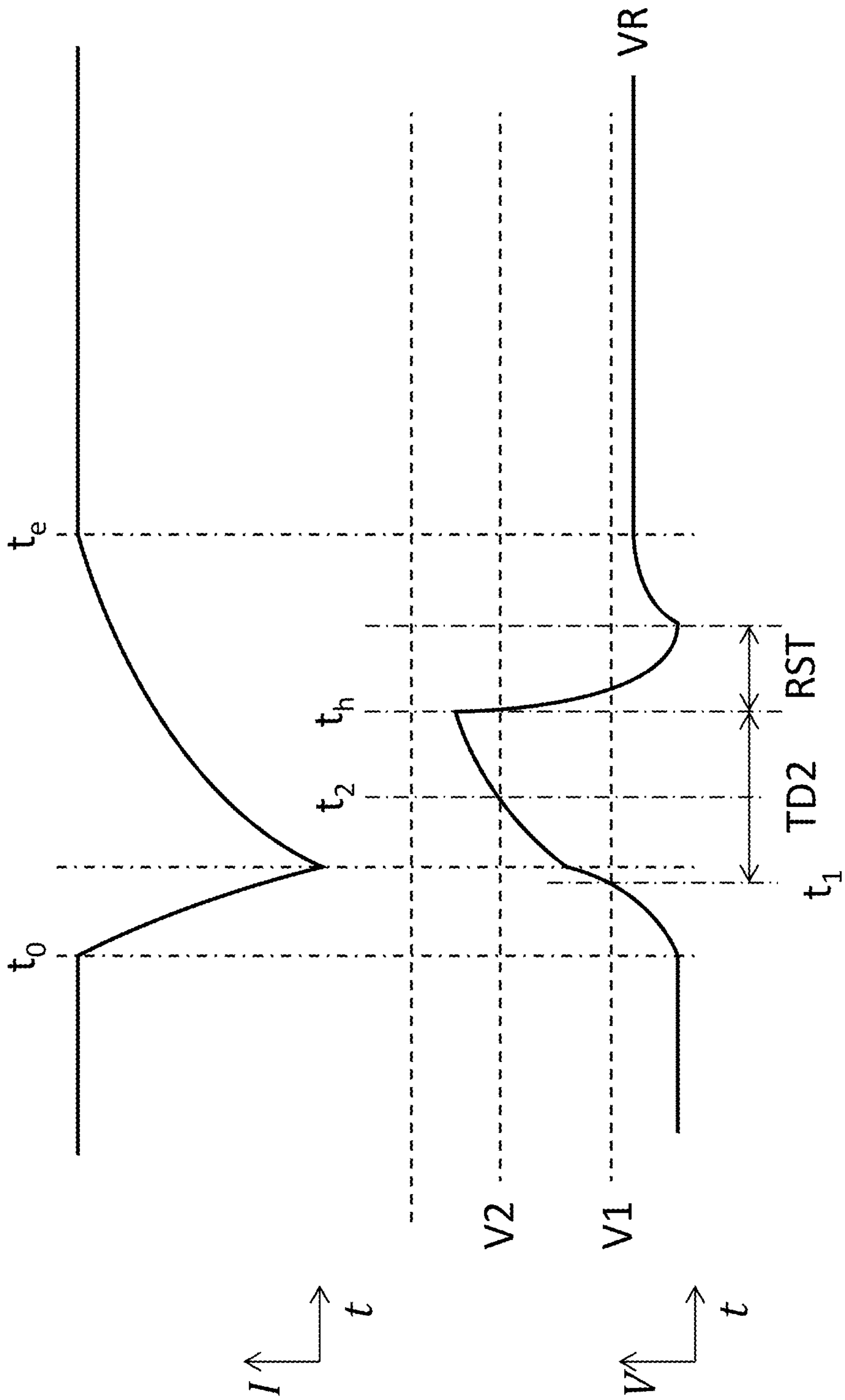


Fig. 18



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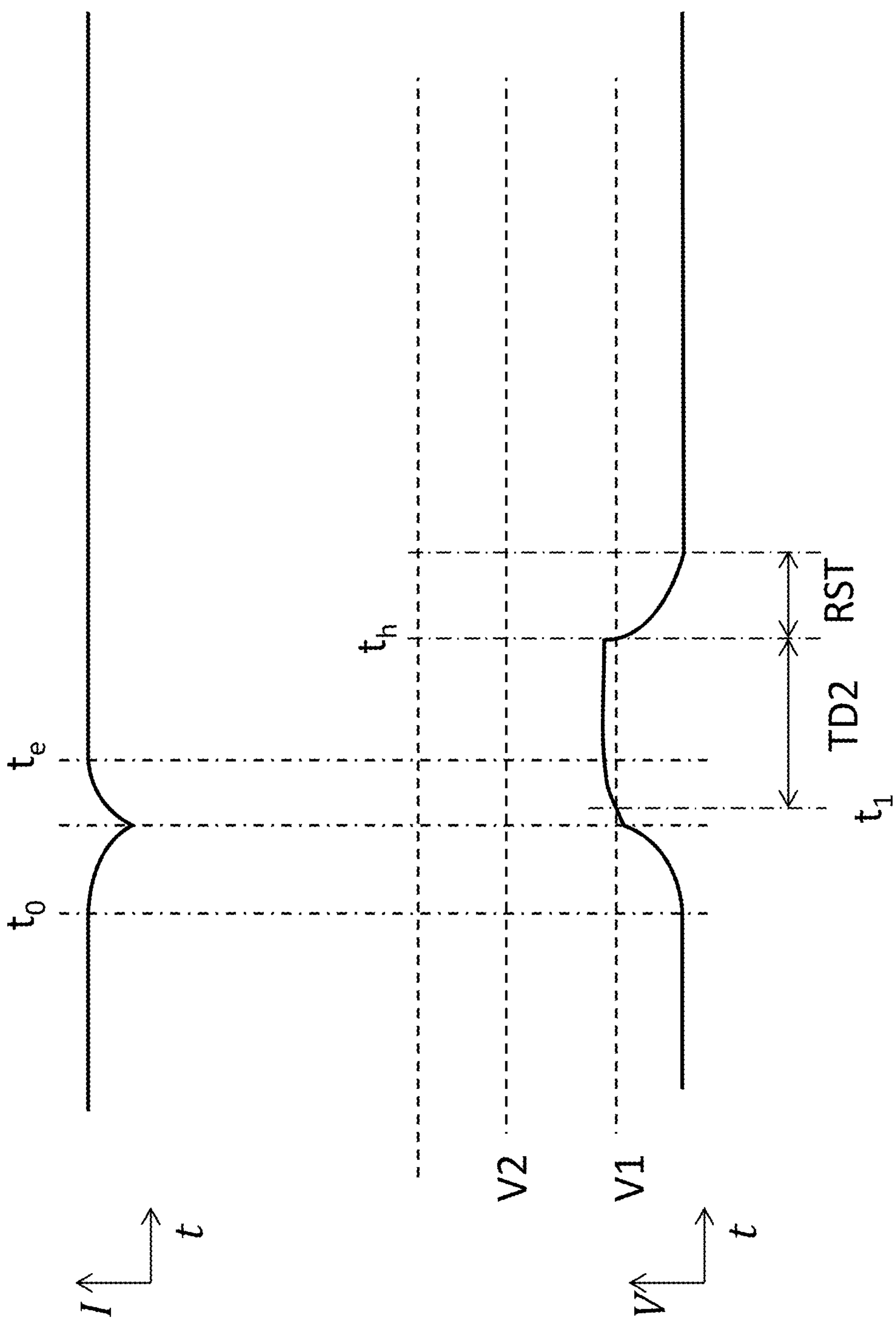

Fig. 20

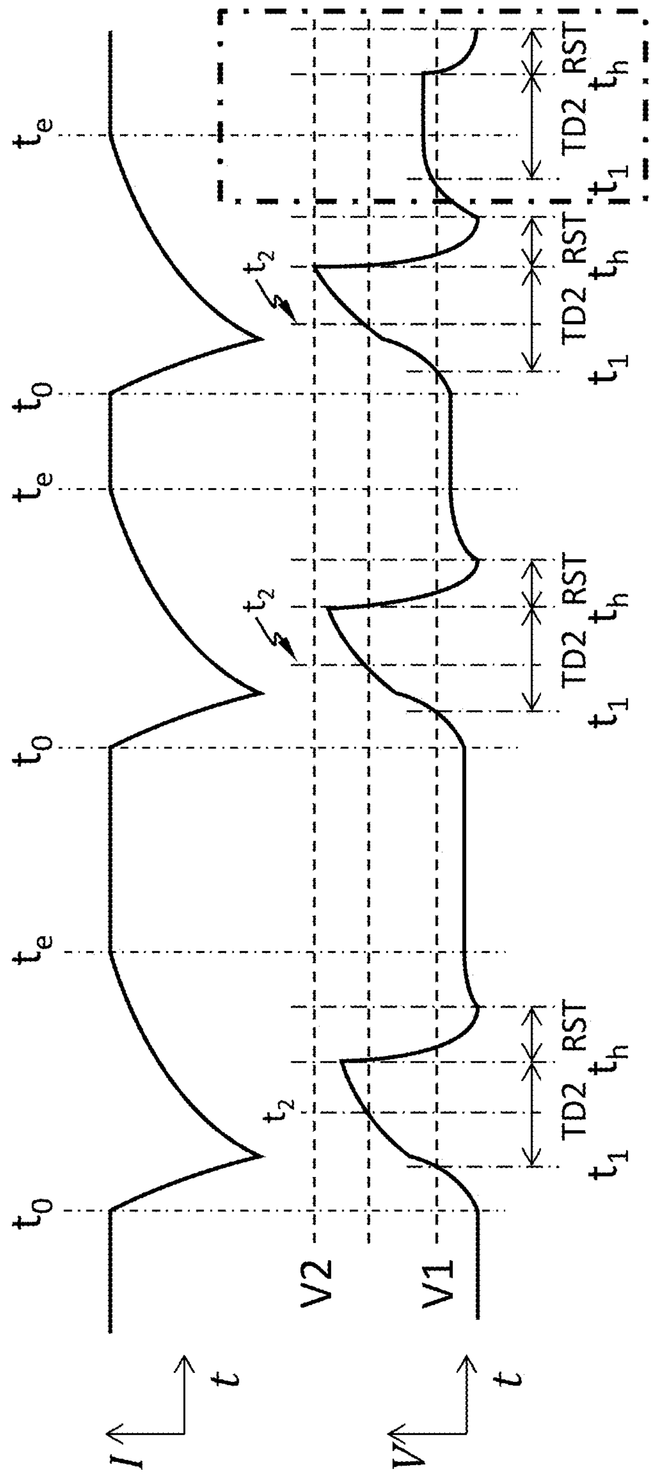

Fig. 21

PACKAGING METHODS OF SEMICONDUCTOR X-RAY DETECTORS

TECHNICAL FIELD

The disclosure herein relates to X-ray detectors, particularly relates to methods of packaging semiconductor X-ray detectors.

BACKGROUND

X-ray detectors may be devices used to measure the flux, spatial distribution, spectrum or other properties of X-rays.

X-ray detectors may be used for many applications. One important application is imaging. X-ray imaging is a radiography technique and can be used to reveal the internal structure of a non-uniformly composed and opaque object such as the human body.

Early X-ray detectors for imaging include photographic plates and photographic films. A photographic plate may be a glass plate with a coating of light-sensitive emulsion. Although photographic plates were replaced by photographic films, they may still be used in special situations due to the superior quality they offer and their extreme stability. A photographic film may be a plastic film (e.g., a strip or sheet) with a coating of light-sensitive emulsion.

In the **1980***s*, photostimulable phosphor plates (PSP plates) became available. A PSP plate may contain a phosphor material with color centers in its lattice. When the PSP plate is exposed to X-ray, electrons excited by X-ray are trapped in the color centers until they are stimulated by a laser beam scanning over the plate surface. As the plate is scanned by laser, trapped excited electrons give off light, which is collected by a photomultiplier tube. The collected light is converted into a digital image. In contrast to photographic plates and photographic films, PSP plates can be reused.

Another kind of X-ray detectors are X-ray image intensifiers. Components of an X-ray image intensifier are usually sealed in a vacuum. In contrast to photographic plates, photographic films, and PSP plates, X-ray image intensifiers may produce real-time images, i.e., do not require post-exposure processing to produce images. X-ray first hits an input phosphor (e.g., cesium iodide) and is converted to visible light. The visible light then hits a photocathode (e.g., a thin metal layer containing cesium and antimony compounds) and causes emission of electrons. The number of emitted electrons is proportional to the intensity of the incident X-ray. The emitted electrons are projected, through electron optics, onto an output phosphor and cause the output phosphor to produce a visible-light image.

Scintillators operate somewhat similarly to X-ray image intensifiers in that scintillators (e.g., sodium iodide) absorb X-ray and emit visible light, which can then be detected by a suitable image sensor for visible light. In scintillators, the visible light spreads and scatters in all directions and thus reduces spatial resolution. Reducing the scintillator thickness helps to improve the spatial resolution but also reduces absorption of X-ray. A scintillator thus has to strike a compromise between absorption efficiency and resolution.

Semiconductor X-ray detectors largely overcome this problem by direct conversion of X-ray into electric signals. A semiconductor X-ray detector may include a semiconductor layer that absorbs X-ray in wavelengths of interest. When an X-ray photon is absorbed in the semiconductor layer, multiple charge carriers (e.g., electrons and holes) are generated and swept under an electric field towards electrical contacts on the semiconductor layer. Cumbersome heat management required in currently available semiconductor X-ray detectors (e.g., Medipix) can make a detector with a large area and a large number of pixels difficult or impossible to produce.

SUMMARY

Disclosed herein is a method for making an apparatus suitable for detecting X-ray, the method comprising: bonding a plurality of chips to a substrate; wherein the substrate comprises an X-ray absorption layer comprising a first plurality of electrical contacts; wherein each of the plurality of chips comprises an electronic layer comprising a second plurality of electrical contacts and an electronic system configured to process or interpret signals generated by X-ray photons incident on the X-ray absorption layer; aligning the first plurality of electrical contacts to the second plurality of electrical contacts; mounting the chips to the substrate such that the first plurality of electrical contacts are electrically connected to the second plurality of electrical contacts; wherein the second plurality of electrical contacts are configured to feed the signals to the electronic system.

According to an embodiment, the method further comprises attaching the plurality of chips to a support wafer.

According to an embodiment, the plurality of chips are attached to the support wafer with an adhesive.

According to an embodiment, the plurality of chips are attached to the support wafer after the plurality of chips are mounted to the substrate.

According to an embodiment, the plurality of chips are mounted to a second substrate.

According to an embodiment, the method further comprises removing the support wafer.

According to an embodiment, removing the support wafer comprises grinding or etching the support wafer.

According to an embodiment, the method further comprises encapsulating the plurality of chips in a matrix.

According to an embodiment, the matrix comprises a polymer or glass.

According to an embodiment, the matrix fills gaps between the chips.

According to an embodiment, the method further comprises exposing a surface of each of the chips.

According to an embodiment, mounting the chips to the substrate comprises mounting the chips encapsulated in the matrix.

According to an embodiment, the electronic layer comprises vias extending to a surface opposite to the X-ray absorption layer.

According to an embodiment, the method further comprises aligning the vias to contact pads on an interposer substrate, and bonding the chips to the interposer substrate such that the vias are electrically connected to the contact pads.

According to an embodiment, the interposer substrate comprises transmission lines electrically connected to the contact pads and configured to route a signal on the contact pads to bonding pads on an edge of the interposer substrate.

According to an embodiment, the method further comprises mounting the interposer substrate to a printed circuit board or positioning the interposer substrate side-by-side with a printed circuit board.

According to an embodiment, the electronic layer comprises a third plurality of electrical contacts configured to read output from the electronic system or to provide power or a reference voltage to the electronic system.

According to an embodiment, the X-ray absorption layer comprises a fourth plurality of electrical contacts configured to connect with the third electrical contacts when the chips are mounted to the substrate.

According to an embodiment, the X-ray absorption layer further comprises transmission lines configured to route a signal at the fourth plurality of electrical contacts to bonding pads on the X-ray absorption layer.

BRIEF DESCRIPTION OF FIGURES

FIG. **1**A schematically shows a cross-sectional view of the detector, according to an embodiment.

FIG. **1**B schematically shows a detailed cross-sectional view of the detector, according to an embodiment.

FIG. **1**C schematically shows an alternative detailed cross-sectional view of the detector, according to an embodiment.

FIG. **2** schematically shows that the device may have an array of pixels, according to an embodiment.

FIG. **3** schematically shows a cross-sectional view of an electronics layer in the detector, according to an embodiment.

FIG. **4**A-FIG. **4**C schematically show a process of packaging the detector **100**, according to an embodiment.

FIG. **5**A-FIG. **5**F schematically show a process of mounting a plurality of chips onto a substrate, according to an embodiment.

FIG. **6**A-FIG. **6**E schematically show a process of mounting a plurality of chips onto a substrate, according to an embodiment.

FIG. **7**A-FIG. **7**C schematically show a process of mounting a plurality of chips onto a substrate, according to an embodiment.

FIG. **8**A-FIG. **8**E schematically show a process of mounting a plurality of chips onto a substrate, according to an embodiment.

FIG. **8**F-**8**I schematically show routing of signal in the X-ray absorption layer and the electronic layer.

FIG. **9** schematically shows a system comprising the semiconductor X-ray detector described herein, suitable for medical imaging such as chest X-ray radiography, abdominal X-ray radiography, etc., according to an embodiment

FIG. **10** schematically shows a system comprising the semiconductor X-ray detector described herein suitable for dental X-ray radiography, according to an embodiment.

FIG. **11** schematically shows a cargo scanning or non-intrusive inspection (NII) system comprising the semiconductor X-ray detector described herein, according to an embodiment.

FIG. **12** schematically shows another cargo scanning or non-intrusive inspection (NII) system comprising the semiconductor X-ray detector described herein, according to an embodiment.

FIG. **13** schematically shows a full-body scanner system comprising the semiconductor X-ray detector described herein, according to an embodiment.

FIG. **14** schematically shows an X-ray computed tomography (X-ray CT) system comprising the semiconductor X-ray detector described herein, according to an embodiment.

FIG. **15** schematically shows an electron microscope comprising the semiconductor X-ray detector described herein, according to an embodiment.

FIG. **16**A and FIG. **16**B each show a component diagram of an electronic system of the detector in FIG. **1**A or FIG. **1**B, according to an embodiment.

FIG. **17** schematically shows a temporal change of the electric current flowing through an electrode (upper curve) of a diode or an electrical contact of a resistor of an X-ray absorption layer exposed to X-ray, the electric current caused by charge carriers generated by an X-ray photon incident on the X-ray absorption layer, and a corresponding temporal change of the voltage of the electrode (lower curve), according to an embodiment.

FIG. **18** schematically shows a temporal change of the electric current flowing through the electrode (upper curve) caused by noise (e.g., dark current), and a corresponding temporal change of the voltage of the electrode (lower curve), in the electronic system operating in the way shown in FIG. **8**, according to an embodiment.

FIG. **19** schematically shows a temporal change of the electric current flowing through an electrode (upper curve) of the X-ray absorption layer exposed to X-ray, the electric current caused by charge carriers generated by an X-ray photon incident on the X-ray absorption layer, and a corresponding temporal change of the voltage of the electrode (lower curve), when the electronic system operates to detect incident X-ray photons at a higher rate, according to an embodiment.

FIG. **20** schematically shows a temporal change of the electric current flowing through the electrode (upper curve) caused by noise (e.g., dark current), and a corresponding temporal change of the voltage of the electrode (lower curve), in the electronic system operating in the way shown in FIG. **10**, according to an embodiment.

FIG. **21** schematically shows a temporal change of the electric current flowing through the electrode (upper curve) caused by charge carriers generated by a series of X-ray photons incident on the X-ray absorption layer, and a corresponding temporal change of the voltage of the electrode, in the electronic system operating in the way shown in FIG. **10** with RST expires before t_e, according to an embodiment.

DETAILED DESCRIPTION

FIG. **1**A schematically shows a cross-sectional view of the detector **100**, according to an embodiment. The detector **100** may include an X-ray absorption layer **110** and an electronics layer **120** (e.g., an ASIC) for processing or analyzing electrical signals incident X-ray generates in the X-ray absorption layer **110**. In an embodiment, the detector **100** does not comprise a scintillator. The X-ray absorption layer **110** may include a semiconductor material such as, silicon, germanium, GaAs, CdTe, CdZnTe, or a combination thereof. The semiconductor may have a high mass attenuation coefficient for the X-ray energy of interest.

As shown in a detailed cross-sectional view of the detector **100** in FIG. **1**B, according to an embodiment, the X-ray absorption layer **110** may include one or more diodes (e.g., p-i-n or p-n) formed by a first doped region **111**, one or more discrete regions **114** of a second doped region **113**. The second doped region **113** may be separated from the first doped region **111** by an optional the intrinsic region **112**. The discrete portions **114** are separated from one another by the first doped region **111** or the intrinsic region **112**. The first doped region **111** and the second doped region **113** have opposite types of doping (e.g., region **111** is p-type and region **113** is n-type, or region **111** is n-type and region **113** is p-type). In the example in FIG. **1**B, each of the discrete regions **114** of the second doped region **113** forms a diode with the first doped region **111** and the optional intrinsic region **112**. Namely, in the example in FIG. **1**B, the X-ray absorption layer **110** has a plurality of diodes having the first doped region **111** as a shared electrode. The first doped region **111** may also have discrete portions.

When an X-ray photon hits the X-ray absorption layer **110** including diodes, the X-ray photon may be absorbed and generate one or more charge carriers by a number of mechanisms. An X-ray photon may generate 10 to 100000 charge carriers. The charge carriers may drift to the electrodes of one of the diodes under an electric field. The field may be an external electric field. The electrical contact **119**B may include discrete portions each of which is in electrical contact with the discrete regions **114**. In an embodiment, the charge carriers may drift in directions such that the charge carriers generated by a single X-ray photon are not substantially shared by two different discrete regions **114** ("not substantially shared" here means less than 2%, less than 0.5%, less than 0.1%, or less than 0.01% of these charge carriers flow to a different one of the discrete regions **114** than the rest of the charge carriers). Charge carriers generated by an X-ray photon incident around the footprint of one of these discrete regions **114** are not substantially shared with another of these discrete regions **114**. A pixel **150** associated with a discrete region **114** may be an area around the discrete region **114** in which substantially all (more than 98%, more than 99.5%, more than 99.9%, or more than 99.99% of) charge carriers generated by an X-ray photon incident therein flow to the discrete region **114**. Namely, less than 2%, less than 1%, less than 0.1%, or less than 0.01% of these charge carriers flow beyond the pixel.

As shown in an alternative detailed cross-sectional view of the detector **100** in FIG. **1**C, according to an embodiment, the X-ray absorption layer **110** may include a resistor of a semiconductor material such as, silicon, germanium, GaAs, CdTe, CdZnTe, or a combination thereof, but does not include a diode. The semiconductor may have a high mass attenuation coefficient for the X-ray energy of interest.

When an X-ray photon hits the X-ray absorption layer **110** including a resistor but not diodes, it may be absorbed and generate one or more charge carriers by a number of mechanisms. An X-ray photon may generate 10 to 100000 charge carriers. The charge carriers may drift to the electrical contacts **119**A and **119**B under an electric field. The field may be an external electric field. The electrical contact **119**B includes discrete portions. In an embodiment, the charge carriers may drift in directions such that the charge carriers generated by a single X-ray photon are not substantially shared by two different discrete portions of the electrical contact **119**B ("not substantially shared" here means less than 2%, less than 0.5%, less than 0.1%, or less than 0.01% of these charge carriers flow to a different one of the discrete portions than the rest of the charge carriers). Charge carriers generated by an X-ray photon incident around the footprint of one of these discrete portions of the electrical contact **119**B are not substantially shared with another of these discrete portions of the electrical contact **119**B. A pixel **150** associated with a discrete portion of the electrical contact **119**B may be an area around the discrete portion in which substantially all (more than 98%, more than 99.5%, more than 99.9% or more than 99.99% of) charge carriers generated by an X-ray photon incident therein flow to the discrete portion of the electrical contact **119**B. Namely, less than 2%, less than 0.5%, less than 0.1%, or less than 0.01% of these charge carriers flow beyond the pixel associated with the one discrete portion of the electrical contact **119**B.

The electronics layer **120** may include an electronic system **121** suitable for processing or interpreting signals generated by X-ray photons incident on the X-ray absorption layer **110**. The electronic system **121** may include an analog circuitry such as a filter network, amplifiers, integrators, and comparators, or a digital circuitry such as a microprocessors, and memory. The electronic system **121** may include components shared by the pixels or components dedicated to a single pixel. For example, the electronic system **121** may include an amplifier dedicated to each pixel and a microprocessor shared among all the pixels. The electronic system **121** may be electrically connected to the pixels by vias **131**. Space among the vias may be filled with a filler material **130**, which may increase the mechanical stability of the connection of the electronics layer **120** to the X-ray absorption layer **110**. Other bonding techniques are possible to connect the electronic system **121** to the pixels without using vias.

FIG. **2** schematically shows that the detector **100** may have an array of pixels **150**. The array may be a rectangular array, a honeycomb array, a hexagonal array or any other suitable array. Each pixel **150** may be configured to detect an X-ray photon incident thereon, measure the energy of the X-ray photon, or both. For example, each pixel **150** may be configured to count numbers of X-ray photons incident thereon whose energy falls in a plurality of bins, within a period of time. All the pixels **150** may be configured to count the numbers of X-ray photons incident thereon within a plurality of bins of energy within the same period of time. Each pixel **150** may have its own analog-to-digital converter (ADC) configured to digitize an analog signal representing the energy of an incident X-ray photon into a digital signal. The ADC may have a resolution of 10 bits or higher. Each pixel **150** may be configured to measure its dark current, such as before or concurrently with each X-ray photon incident thereon. Each pixel **150** may be configured to deduct the contribution of the dark current from the energy of the X-ray photon incident thereon. The pixels **150** may be configured to operate in parallel. For example, when one pixel **150** measures an incident X-ray photon, another pixel **150** may be waiting for an X-ray photon to arrive. The pixels **150** may be but do not have to be individually addressable.

FIG. **3** schematically shows the electronics layer **120** according to an embodiment. The electronic layer **120** comprises a substrate **122** having a first surface **124** and a second surface **128**. A "surface" as used herein is not necessarily exposed, but can be buried wholly or partially. The electronic layer **120** comprises one or more electric contacts **125** on the first surface **124**. The one or more electric contacts **125** may be configured to be electrically connected to one or more electrical contacts **119**B of the X-ray absorption layer **110**. The electronics system **121** may be in or on the substrate **122**. The electronic layer **120** comprises one or more vias **126** extending from the first surface **124** to the second surface **128**.

The substrate **122** may be a thinned substrate. For example, the substrate may have at thickness of 750 microns or less, 200 microns or less, 100 microns or less, 50 microns or less, 20 microns or less, or 5 microns or less. The substrate **122** may be a silicon substrate or a substrate or other suitable semiconductor or insulator. The substrate **122** may be produced by grinding a thicker substrate to a desired thickness.

The one or more electric contacts **125** may be a layer of metal or doped semiconductor. For example, the electric contacts **125** may be gold, copper, platinum, palladium, doped silicon, etc.

The vias **126** pass through the substrate **122** and electrically connect electrical components (e.g., the electrical contacts **125** and the electronic system **121**) on the first surface **124** to electrical components on the second surface

128. The vias **126** are sometimes referred to as "through-silicon vias" although they may be fabricated in substrates of materials other than silicon. Multiple electronical components on the first surface **124** may share one via **126**.

FIG. **3** further schematically shows bonding between the X-ray absorption layer **110** and the electronic layer **120** at the electrical contact **119**B and the electrical contacts **125**. The bonding may be by a suitable technique such as direct bonding or flip chip bonding.

Direct bonding is a wafer bonding process without any additional intermediate layers (e.g., solder bumps). The bonding process is based on chemical bonds between two surfaces. Direct bonding may be at elevated temperature but not necessarily so.

Flip chip bonding uses solder bumps **199** deposited onto contact pads (e.g., the electrical contact **119**B of the X-ray absorption layer **110** or the electrical contacts **125**). Either the X-ray absorption layer **110** or the electronic layer **120** is flipped over and the electrical contact **119**B of the X-ray absorption layer **110** are aligned to the electrical contacts **125**. The solder bumps **199** may be melted to solder the electrical contact **119**B and the electrical contacts **125** together. Any void space among the solder bumps **199** may be filled with an insulating material.

FIG. **4**A-FIG. **4**C schematically show a process of packaging the detector **100**, according to an embodiment.

FIG. **4**A schematically shows that multiple chips are obtained. Each of the chips includes the electronic layer **120** and the electrical contacts **125**. The chips may be obtained by dicing a wafer with multiple dies.

FIG. **4**B schematically shows that the electrical contacts **125** of the chips are aligned to the electrical contacts **119**B of the X-ray absorption layer **110**. In this view, the electrical contacts **125** are not visible because they face the X-ray absorption layer **110** but the electrical contacts **119**B are visible.

FIG. **4**C schematically shows that the chips are bonded to the X-ray absorption layer **110** using a suitable bonding method. The electrical contacts **119**B of the X-ray absorption layer **110** are now electrically connected to the electrical contacts **125** of the electronic layer **120**.

FIG. **5**A-FIG. **5**F schematically show a process of mounting a plurality of chips onto a substrate, according to an embodiment. This process may be used in mounting the chips depicted in FIG. **4**C.

FIG. **5**A schematically shows that chips **810** (e.g., the chip including the electronic layer **120** as shown in FIG. **4**C) may be obtained and placed into an array or any other suitable arrangement.

FIG. **5**B schematically shows that the chips **810** are attached to a support wafer **820**. For example, the chips **810** may be attached with an adhesive.

FIG. **5**C schematically shows that the chips **810** are mounted to the substrate **830** while still attached to the support wafer **820**. The substrate **830** can be the X-ray absorption layer **110** depicted in FIG. **4**C.

FIG. **5**D schematically shows an alternative, where the chips **810** attached to a single support wafer **820** may be mounted to multiple substrates **830**.

FIG. **5**E schematically shows an alternative, where the chips **810** are mounted to multiple substrates **830** but the boundaries among the chips **810** and the boundaries among the substrate **830** may not coincide. Namely, the electrical contacts **125** on a given chip **810** may be connected to different substrates **830** and the electrical contacts **119**B on a given substrate **830** may be connected to different chips **810**. The chips **810** and the substrates **830** may both include transmission lines and contacts configured to connect the transmission lines in them. For clarity, some components of the chips **810** and the substrates **830** are omitted in FIG. **5**E.

FIG. **5**F schematically shows that the support wafer **820** is removed. For example, the support wafer **820** may be ground away, etched away, or separated from the chips **810**.

FIG. **6**A-FIG. **6**E schematically show a process of mounting a plurality of chips onto a substrate, according to an embodiment. This process may be used in mounting the chips depicted in FIG. **4**C.

FIG. **6**A schematically shows that chips **910** (e.g., the chip including the electronic layer **120** as shown in FIG. **4**C) may be obtained and placed into an array or any other suitable arrangement on a support wafer **920**.

FIG. **6**B schematically shows that the chips **910** are encapsulated in a matrix **925**. The matrix **925** is supported on the support wafer **920**. The matrix **925** may be a polymer, glass or other suitable material. The matrix **925** may fill gaps between the chips **910**.

FIG. **6**C schematically shows that the support wafer **920** is removed. For example, the support wafer **920** may be ground away, etched away, or separated from the chips **910**. The matrix **925** supports the chips **910** after removal of the support wafer **920**. The surfaces of the chips **910** contacting the support wafer **920** may be exposed by removal of the support wafer **920**.

FIG. **6**D schematically shows the encapsulated chips **910** are aligned to the substrate **930**. The chips **910** may be then aligned with the substrate **930** (e.g. the X-ray absorption layer **110** depicted in FIG. **4**C), or structures thereon (e.g., electrical contacts).

FIG. **6**E schematically shows that the encapsulated chips **910** are attached to the substrate **930**.

FIG. **7**A schematically shows that the chips including the electronic layer **120** may have vias **126** extending to a surface opposite to the X-ray absorption layer **110**, to which the chips are mounted.

FIG. **7**B schematically shows that the vias **126** may be aligned to contacts pads **410** on interposer substrate **400** (e.g., a silicon wafer).

FIG. **7**C schematically shows that the electronic layers **120** of the chips are bonded to the interposer substrate **400**. After the bonding, the vias **126** are electrically connected contacts pads **410**. The interposer substrate **400** may have transmission lines buried in the interposer substrate **400** or on the surface on the interposer substrate **400**. The transmission lines are electrically connected to the contact pads **410** and are configured to route signals on the contact pads **410** to bonding pads **430** on the edge of the interposer substrate **400**. The interposer substrate **400** is mounted to a printed circuit board **500**. Alternatively, the interposer substrate **400** may be positioned side by side with a printed circuit board **500**. More than one interposer substrate may be mounted to the same printed circuit board. The electrical contact between the interposer substrate **400** and the printed circuit board **500** may be made with wire bonding.

FIG. **8**A schematically shows that the chips including the electronic layer **120** are bonded to the X-ray absorption layer **110**.

FIG. **8**B schematically shows that the X-ray absorption layer **110** is optionally mounted to a printed circuit board **600**. Alternatively, the X-ray absorption layer **110** may be optionally positioned side by side with a printed circuit board **600**. Electrical contact between the X-ray absorption layer **110** and the printed circuit board **600** may be made with wire bonding.

FIG. **8**C schematically shows that the first surface **124** of the electronic layer **120** has a set of electrical contacts **129** in addition to the electrical contacts **125**. The electrical contacts **129** may function as I/O interface to the electronic system **121**. For example the electrical contacts **129** may be configured to read output from the electronic system **121**, controlling the electronic system **121**, or provide power or reference voltages to the electronic system **121**.

As schematically shown in FIG. **8**D and FIG. **8**E, the X-ray absorption layer **110** may have electrical contacts **119**C configured to connect with the electrical contacts **129** after the chips are mounted to the X-ray absorption layer **110**. The X-ray absorption layer **110** may have transmission lines **119**E configured to route signals at the electrical contacts **119**C to bonding pads **119**D near the edge of the X-ray absorption layer **110**. The bonding pads **119**D may be used to make electrical connections to a PCB or to another integrated circuit. The electrical contacts **119**C may be at locations where some of the electrical contact **119**B would otherwise be, as shown in FIG. **8**D. The electrical contacts **119**C may be located in area between the electrical contact **119**B, as shown in FIG. **8**E.

FIGS. **8**F-**8**I schematically show routing of signal in the X-ray absorption layer **110** and the electronic layer **120**. The features of the X-ray absorption layer **110** such as the electrical contacts **119**A and **119**B and the discrete regions **114** are usually on the scale of micrometers. The features of the X-ray absorption layer **110** may be fabricated by doing whole-wafer lithography. The features of the electronic layer **120** are usually much smaller and may not be fabricated by doing whole-wafer lithography. Instead, the features of the electronic layer **120** may be fabricated by doing die-by-die lithography. Therefore, making long-distance transmission lines (e.g., across a whole 8" wafer) on the X-ray absorption layer **110** is much easier than making transmission lines across boundaries between the dies.

As shown in FIG. **8**F, where multiples chips containing the X-ray absorption layer **110** and multiple chips containing the electronic layer **120** are attached, the chips containing the X-ray absorption layer **110** may include electrical contacts **891**, bonding pads **892**, transmission lines **893** connecting the electrical contacts **891** to the bonding pads **892**; the chips containing the electronic layer **120** may include electrical contacts **894** and transmission lines **895** connecting among the electrical contacts **894**. The transmissions lines **895** do not cross boundaries of dies. The electrical contacts **891** and the electrical contacts **894** may be aligned and connected such that signals are bridged across gaps between the chips containing the electronic layer **120** through the transmission lines **893** and across gaps between the chips containing the X-ray absorption layer **110** through the transmission lines **895**.

As shown in FIG. **8**G, where multiples chips containing the X-ray absorption layer **110** and a wafer containing the electronic layer **120** are attached, the chips containing the X-ray absorption layer **110** may include electrical contacts **891**, bonding pads **892**, transmission lines **893** connecting the electrical contacts **891** to the bonding pads **892**; the wafer containing the electronic layer **120** may include electrical contacts **894** and transmission lines **895** connecting among the electrical contacts **894**. The transmissions lines **895** do not cross boundaries of dies. The electrical contacts **891** and the electrical contacts **894** may be aligned and connected such that signals are bridged across gaps between the chips containing the X-ray absorption layer **110** through the transmission lines **895**.

As shown in FIG. **8**H, where a wafer containing the X-ray absorption layer **110** and multiple chips containing the electronic layer **120** are attached, the wafer containing the X-ray absorption layer **110** may include electrical contacts **891**, bonding pads **892**, transmission lines **893** connecting the electrical contacts **891** to the bonding pads **892**; the chips containing the electronic layer **120** may include electrical contacts **894** but do not have to include transmission lines connecting among the electrical contacts **894**. The electrical contacts **891** and the electrical contacts **894** may be aligned and connected such that signals are bridged across gaps between the chips containing the electronic layer **120** through the transmission lines **893**.

As shown in FIG. **8**I, where a wafer containing the X-ray absorption layer **110** and a wafer containing the electronic layer **120** are attached, the wafer containing the X-ray absorption layer **110** may include electrical contacts **891**, bonding pads **892**, transmission lines **893** connecting the electrical contacts **891** to the bonding pads **892**; the wafer containing the electronic layer **120** may include electrical contacts **894** but do not have to include transmission lines connecting among the electrical contacts **894**. The electrical contacts **891** and the electrical contacts **894** may be aligned and connected such that signals from the electronic layer **120** are routed through the transmission lines **893**.

FIG. **9** schematically shows a system comprising the semiconductor X-ray detector **100** described herein. The system may be used for medical imaging such as chest X-ray radiography, abdominal X-ray radiography, etc. The system comprises an X-ray source **1201**. X-ray emitted from the X-ray source **1201** penetrates an object **1202** (e.g., a human body part such as chest, limb, abdomen), is attenuated by different degrees by the internal structures of the object **1202** (e.g., bones, muscle, fat and organs, etc.), and is projected to the semiconductor X-ray detector **100**. The semiconductor X-ray detector **100** forms an image by detecting the intensity distribution of the X-ray.

FIG. **10** schematically shows a system comprising the semiconductor X-ray detector **100** described herein. The system may be used for medical imaging such as dental X-ray radiography. The system comprises an X-ray source **1301**. X-ray emitted from the X-ray source **1301** penetrates an object **1302** that is part of a mammal (e.g., human) mouth. The object **1302** may include a maxilla bone, a palate bone, a tooth, the mandible, or the tongue. The X-ray is attenuated by different degrees by the different structures of the object **1302** and is projected to the semiconductor X-ray detector **100**. The semiconductor X-ray detector **100** forms an image by detecting the intensity distribution of the X-ray. Teeth absorb X-ray more than dental caries, infections, periodontal ligament. The dosage of X-ray radiation received by a dental patient is typically small (around 0.150 mSv for a full mouth series).

FIG. **11** schematically shows a cargo scanning or non-intrusive inspection (NII) system comprising the semiconductor X-ray detector **100** described herein. The system may be used for inspecting and identifying goods in transportation systems such as shipping containers, vehicles, ships, luggage, etc. The system comprises an X-ray source **1401**. X-ray emitted from the X-ray source **1401** may backscatter from an object **1402** (e.g., shipping containers, vehicles, ships, etc.) and be projected to the semiconductor X-ray detector **100**. Different internal structures of the object **1402** may backscatter X-ray differently. The semiconductor X-ray detector **100** forms an image by detecting the intensity distribution of the backscattered X-ray and/or energies of the backscattered X-ray photons.

FIG. **12** schematically shows another cargo scanning or non-intrusive inspection (NII) system comprising the semiconductor X-ray detector **100** described herein. The system may be used for luggage screening at public transportation stations and airports. The system comprises an X-ray source **1501**. X-ray emitted from the X-ray source **1501** may penetrate a piece of luggage **1502**, be differently attenuated by the contents of the luggage, and projected to the semiconductor X-ray detector **100**. The semiconductor X-ray detector **100** forms an image by detecting the intensity distribution of the transmitted X-ray. The system may reveal contents of luggage and identify items forbidden on public transportation, such as firearms, narcotics, edged weapons, flammables.

FIG. **13** schematically shows a full-body scanner system comprising the semiconductor X-ray detector **100** described herein. The full-body scanner system may detect objects on a person's body for security screening purposes, without physically removing clothes or making physical contact. The full-body scanner system may be able to detect non-metal objects. The full-body scanner system comprises an X-ray source **1601**. X-ray emitted from the X-ray source **1601** may backscatter from a human **1602** being screened and objects thereon, and be projected to the semiconductor X-ray detector **100**. The objects and the human body may backscatter X-ray differently. The semiconductor X-ray detector **100** forms an image by detecting the intensity distribution of the backscattered X-ray. The semiconductor X-ray detector **100** and the X-ray source **1601** may be configured to scan the human in a linear or rotational direction.

FIG. **14** schematically shows an X-ray computed tomography (X-ray CT) system. The X-ray CT system uses computer-processed X-rays to produce tomographic images (virtual "slices") of specific areas of a scanned object. The tomographic images may be used for diagnostic and therapeutic purposes in various medical disciplines, or for flaw detection, failure analysis, metrology, assembly analysis and reverse engineering. The X-ray CT system comprises the semiconductor X-ray detector **100** described herein and an X-ray source **1701**. The semiconductor X-ray detector **100** and the X-ray source **1701** may be configured to rotate synchronously along one or more circular or spiral paths.

FIG. **15** schematically shows an electron microscope. The electron microscope comprises an electron source **1801** (also called an electron gun) that is configured to emit electrons. The electron source **1801** may have various emission mechanisms such as thermionic, photocathode, cold emission, or plasmas source. The emitted electrons pass through an electronic optical system **1803**, which may be configured to shape, accelerate, or focus the electrons. The electrons then reach a sample **1802** and an image detector may form an image therefrom. The electron microscope may comprise the semiconductor X-ray detector **100** described herein, for performing energy-dispersive X-ray spectroscopy (EDS). EDS is an analytical technique used for the elemental analysis or chemical characterization of a sample. When the electrons incident on a sample, they cause emission of characteristic X-rays from the sample. The incident electrons may excite an electron in an inner shell of an atom in the sample, ejecting it from the shell while creating an electron hole where the electron was. An electron from an outer, higher-energy shell then fills the hole, and the difference in energy between the higher-energy shell and the lower energy shell may be released in the form of an X-ray. The number and energy of the X-rays emitted from the sample can be measured by the semiconductor X-ray detector **100**.

The semiconductor X-ray detector **100** described here may have other applications such as in an X-ray telescope, X-ray mammography, industrial X-ray defect detection, X-ray microscopy or microradiography, X-ray casting inspection, X-ray non-destructive testing, X-ray weld inspection, X-ray digital subtraction angiography, etc. It may be suitable to use this semiconductor X-ray detector **100** in place of a photographic plate, a photographic film, a PSP plate, an X-ray image intensifier, a scintillator, or another semiconductor X-ray detector.

FIG. **16**A and FIG. **16**B each show a component diagram of the electronic system **121**, according to an embodiment. The electronic system **121** may include a first voltage comparator **301**, a second voltage comparator **302**, a counter **320**, a switch **305**, a voltmeter **306** and a controller **310**.

The first voltage comparator **301** is configured to compare the voltage of an electrode of a diode **300** to a first threshold. The diode may be a diode formed by the first doped region **111**, one of the discrete regions **114** of the second doped region **113**, and the optional intrinsic region **112**. Alternatively, the first voltage comparator **301** is configured to compare the voltage of an electrical contact (e.g., a discrete portion of electrical contact **119**B) to a first threshold. The first voltage comparator **301** may be configured to monitor the voltage directly, or calculate the voltage by integrating an electric current flowing through the diode or electrical contact over a period of time. The first voltage comparator **301** may be controllably activated or deactivated by the controller **310**. The first voltage comparator **301** may be a continuous comparator. Namely, the first voltage comparator **301** may be configured to be activated continuously, and monitor the voltage continuously. The first voltage comparator **301** configured as a continuous comparator reduces the chance that the system **121** misses signals generated by an incident X-ray photon. The first voltage comparator **301** configured as a continuous comparator is especially suitable when the incident X-ray intensity is relatively high. The first voltage comparator **301** may be a clocked comparator, which has the benefit of lower power consumption. The first voltage comparator **301** configured as a clocked comparator may cause the system **121** to miss signals generated by some incident X-ray photons. When the incident X-ray intensity is low, the chance of missing an incident X-ray photon is low because the time interval between two successive photons is relatively long. Therefore, the first voltage comparator **301** configured as a clocked comparator is especially suitable when the incident X-ray intensity is relatively low. The first threshold may be 5-10%, 10%-20%, 20-30%, 30-40% or 40-50% of the maximum voltage one incident X-ray photon may generate in the diode or the resistor. The maximum voltage may depend on the energy of the incident X-ray photon (i.e., the wavelength of the incident X-ray), the material of the X-ray absorption layer **110**, and other factors. For example, the first threshold may be 50 mV, 100 mV, 150 mV, or 200 mV.

The second voltage comparator **302** is configured to compare the voltage to a second threshold. The second voltage comparator **302** may be configured to monitor the voltage directly, or calculate the voltage by integrating an electric current flowing through the diode or the electrical contact over a period of time. The second voltage comparator **302** may be a continuous comparator. The second voltage comparator **302** may be controllably activate or deactivated by the controller **310**. When the second voltage comparator

302 is deactivated, the power consumption of the second voltage comparator 302 may be less than 1%, less than 5%, less than 10% or less than 20% of the power consumption when the second voltage comparator 302 is activated. The absolute value of the second threshold is greater than the absolute value of the first threshold. As used herein, the term "absolute value" or "modulus" |x| of a real number x is the non-negative value of x without regard to its sign. Namely,

$$|x| = \begin{cases} x, \text{ if } x \geq 0 \\ -x, \text{ if } x \leq 0 \end{cases}.$$

The second threshold may be 200%-300% of the first threshold. The second threshold may be at least 50% of the maximum voltage one incident X-ray photon may generate in the diode or resistor. For example, the second threshold may be 100 mV, 150 mV, 200 mV, 250 mV or 300 mV. The second voltage comparator 302 and the first voltage comparator 310 may be the same component. Namely, the system 121 may have one voltage comparator that can compare a voltage with two different thresholds at different times.

The first voltage comparator 301 or the second voltage comparator 302 may include one or more op-amps or any other suitable circuitry. The first voltage comparator 301 or the second voltage comparator 302 may have a high speed to allow the system 121 to operate under a high flux of incident X-ray. However, having a high speed is often at the cost of power consumption.

The counter 320 is configured to register a number of X-ray photons reaching the diode or resistor. The counter 320 may be a software component (e.g., a number stored in a computer memory) or a hardware component (e.g., a 4017 IC and a 7490 IC).

The controller 310 may be a hardware component such as a microcontroller and a microprocessor. The controller 310 is configured to start a time delay from a time at which the first voltage comparator 301 determines that the absolute value of the voltage equals or exceeds the absolute value of the first threshold (e.g., the absolute value of the voltage increases from below the absolute value of the first threshold to a value equal to or above the absolute value of the first threshold). The absolute value is used here because the voltage may be negative or positive, depending on whether the voltage of the cathode or the anode of the diode or which electrical contact is used. The controller 310 may be configured to keep deactivated the second voltage comparator 302, the counter 320 and any other circuits the operation of the first voltage comparator 301 does not require, before the time at which the first voltage comparator 301 determines that the absolute value of the voltage equals or exceeds the absolute value of the first threshold. The time delay may expire before or after the voltage becomes stable, i.e., the rate of change of the voltage is substantially zero. The phase "the rate of change of the voltage is substantially zero" means that temporal change of the voltage is less than 0.1%/ns. The phase "the rate of change of the voltage is substantially non-zero" means that temporal change of the voltage is at least 0.1%/ns.

The controller 310 may be configured to activate the second voltage comparator during (including the beginning and the expiration) the time delay. In an embodiment, the controller 310 is configured to activate the second voltage comparator at the beginning of the time delay. The term "activate" means causing the component to enter an operational state (e.g., by sending a signal such as a voltage pulse or a logic level, by providing power, etc.). The term "deactivate" means causing the component to enter a non-operational state (e.g., by sending a signal such as a voltage pulse or a logic level, by cut off power, etc.). The operational state may have higher power consumption (e.g., 10 times higher, 100 times higher, 1000 times higher) than the non-operational state. The controller 310 itself may be deactivated until the output of the first voltage comparator 301 activates the controller 310 when the absolute value of the voltage equals or exceeds the absolute value of the first threshold.

The controller 310 may be configured to cause the number registered by the counter 320 to increase by one, if, during the time delay, the second voltage comparator 302 determines that the absolute value of the voltage equals or exceeds the absolute value of the second threshold.

The controller 310 may be configured to cause the voltmeter 306 to measure the voltage upon expiration of the time delay. The controller 310 may be configured to connect the electrode to an electrical ground, so as to reset the voltage and discharge any charge carriers accumulated on the electrode. In an embodiment, the electrode is connected to an electrical ground after the expiration of the time delay. In an embodiment, the electrode is connected to an electrical ground for a finite reset time period. The controller 310 may connect the electrode to the electrical ground by controlling the switch 305. The switch may be a transistor such as a field-effect transistor (FET).

In an embodiment, the system 121 has no analog filter network (e.g., a RC network). In an embodiment, the system 121 has no analog circuitry.

The voltmeter 306 may feed the voltage it measures to the controller 310 as an analog or digital signal.

The system 121 may include a capacitor module 309 electrically connected to the electrode of the diode 300 or which electrical contact, wherein the capacitor module is configured to collect charge carriers from the electrode. The capacitor module can include a capacitor in the feedback path of an amplifier. The amplifier configured as such is called a capacitive transimpedance amplifier (CTIA). CTIA has high dynamic range by keeping the amplifier from saturating and improves the signal-to-noise ratio by limiting the bandwidth in the signal path. Charge carriers from the electrode accumulate on the capacitor over a period of time ("integration period") (e.g., as shown in FIG. 17, between t_0 to t_1, or t_1-t_2). After the integration period has expired, the capacitor voltage is sampled and then reset by a reset switch. The capacitor module can include a capacitor directly connected to the electrode.

FIG. 17 schematically shows a temporal change of the electric current flowing through the electrode (upper curve) caused by charge carriers generated by an X-ray photon incident on the diode or the resistor, and a corresponding temporal change of the voltage of the electrode (lower curve). The voltage may be an integral of the electric current with respect to time. At time t_0, the X-ray photon hits the diode or the resistor, charge carriers start being generated in the diode or the resistor, electric current starts to flow through the electrode of the diode or the resistor, and the absolute value of the voltage of the electrode or electrical contact starts to increase. At time t_1, the first voltage comparator 301 determines that the absolute value of the voltage equals or exceeds the absolute value of the first threshold V1, and the controller 310 starts the time delay TD1 and the controller 310 may deactivate the first voltage comparator 301 at the beginning of TD1. If the controller 310 is deactivated before t_1, the controller 310 is activated at t_1. During TD1, the controller 310 activates the second voltage comparator 302. The term "during" a time delay as used here means the beginning and the expiration (i.e., the end) and any time in between. For example, the controller 310 may activate the second voltage comparator 302 at the expiration of TD1. If during TD1, the second voltage comparator 302 determines that the absolute value of the voltage equals or exceeds the absolute value of the second threshold at time t_2, the controller 310 causes the number registered by the counter 320 to increase by one. At time t_e, all charge carriers generated by the X-ray photon drift out of the X-ray absorption layer 110. At time t_s, the time delay TD1 expires. In the example of FIG. 17, time t_s is after time t_e; namely TD1 expires after all charge carriers generated by the X-ray photon drift out of the X-ray absorption layer 110. The rate of change of the voltage is thus substantially zero at t_s. The controller 310 may be configured to deactivate the second voltage comparator 302 at expiration of TD1 or at t_2, or any time in between.

The controller 310 may be configured to cause the voltmeter 306 to measure the voltage upon expiration of the time delay TD1. In an embodiment, the controller 310 causes the voltmeter 306 to measure the voltage after the rate of change of the voltage becomes substantially zero after the expiration of the time delay TD1. The voltage at this moment is proportional to the amount of charge carriers generated by an X-ray photon, which relates to the energy of the X-ray photon. The controller 310 may be configured to determine the energy of the X-ray photon based on voltage the voltmeter 306 measures. One way to determine the energy is by binning the voltage. The counter 320 may have a sub-counter for each bin. When the controller 310 determines that the energy of the X-ray photon falls in a bin, the controller 310 may cause the number registered in the sub-counter for that bin to increase by one. Therefore, the system 121 may be able to detect an X-ray image and may be able to resolve X-ray photon energies of each X-ray photon.

After TD1 expires, the controller 310 connects the electrode to an electric ground for a reset period RST to allow charge carriers accumulated on the electrode to flow to the ground and reset the voltage. After RST, the system 121 is ready to detect another incident X-ray photon. Implicitly, the rate of incident X-ray photons the system 121 can handle in the example of FIG. 17 is limited by 1/(TD1+RST). If the first voltage comparator 301 has been deactivated, the controller 310 can activate it at any time before RST expires. If the controller 310 has been deactivated, it may be activated before RST expires.

FIG. 18 schematically shows a temporal change of the electric current flowing through the electrode (upper curve) caused by noise (e.g., dark current, background radiation, scattered X-rays, fluorescent X-rays, shared charges from adjacent pixels), and a corresponding temporal change of the voltage of the electrode (lower curve), in the system 121 operating in the way shown in FIG. 17. At time t_0, the noise begins. If the noise is not large enough to cause the absolute value of the voltage to exceed the absolute value of V1, the controller 310 does not activate the second voltage comparator 302. If the noise is large enough to cause the absolute value of the voltage to exceed the absolute value of V1 at time t_1 as determined by the first voltage comparator 301, the controller 310 starts the time delay TD1 and the controller 310 may deactivate the first voltage comparator 301 at the beginning of TD1. During TD1 (e.g., at expiration of TD1), the controller 310 activates the second voltage comparator 302. The noise is very unlikely large enough to cause the absolute value of the voltage to exceed the absolute value of V2 during TD1. Therefore, the controller 310 does not cause the number registered by the counter 320 to increase. At time t_e, the noise ends. At time t_s, the time delay TD1 expires. The controller 310 may be configured to deactivate the second voltage comparator 302 at expiration of TD1. The controller 310 may be configured not to cause the voltmeter 306 to measure the voltage if the absolute value of the voltage does not exceed the absolute value of V2 during TD1. After TD1 expires, the controller 310 connects the electrode to an electric ground for a reset period RST to allow charge carriers accumulated on the electrode as a result of the noise to flow to the ground and reset the voltage. Therefore, the system 121 may be very effective in noise rejection.

FIG. 19 schematically shows a temporal change of the electric current flowing through the electrode (upper curve) caused by charge carriers generated by an X-ray photon incident on the diode or the resistor, and a corresponding temporal change of the voltage of the electrode (lower curve), when the system 121 operates to detect incident X-ray photons at a rate higher than 1/(TD1+RST). The voltage may be an integral of the electric current with respect to time. At time to, the X-ray photon hits the diode or the resistor, charge carriers start being generated in the diode or the resistor, electric current starts to flow through the electrode of the diode or the electrical contact of resistor, and the absolute value of the voltage of the electrode or the electrical contact starts to increase. At time t_1, the first voltage comparator 301 determines that the absolute value of the voltage equals or exceeds the absolute value of the first threshold V1, and the controller 310 starts a time delay TD2 shorter than TD1, and the controller 310 may deactivate the first voltage comparator 301 at the beginning of TD2. If the controller 310 is deactivated before t_1, the controller 310 is activated at t_1. During TD2 (e.g., at expiration of TD2), the controller 310 activates the second voltage comparator 302. If during TD2, the second voltage comparator 302 determines that the absolute value of the voltage equals or exceeds the absolute value of the second threshold at time t_2, the controller 310 causes the number registered by the counter 320 to increase by one. At time t_e, all charge carriers generated by the X-ray photon drift out of the X-ray absorption layer 110. At time t_h, the time delay TD2 expires. In the example of FIG. 19, time t_h is before time t_e; namely TD2 expires before all charge carriers generated by the X-ray photon drift out of the X-ray absorption layer 110. The rate of change of the voltage is thus substantially non-zero at t_h. The controller 310 may be configured to deactivate the second voltage comparator 302 at expiration of TD2 or at t_2, or any time in between.

The controller 310 may be configured to extrapolate the voltage at t_e from the voltage as a function of time during TD2 and use the extrapolated voltage to determine the energy of the X-ray photon.

After TD2 expires, the controller 310 connects the electrode to an electric ground for a reset period RST to allow charge carriers accumulated on the electrode to flow to the ground and reset the voltage. In an embodiment, RST expires before t_e. The rate of change of the voltage after RST may be substantially non-zero because all charge carriers generated by the X-ray photon have not drifted out of the X-ray absorption layer 110 upon expiration of RST before t_e. The rate of change of the voltage becomes substantially zero after t_e and the voltage stabilized to a residue voltage VR after t_e. In an embodiment, RST expires at or after t_e, and the rate of change of the voltage after RST may be substantially zero because all charge carriers generated by the X-ray photon drift out of the X-ray absorption layer **110** at t_e. After RST, the system **121** is ready to detect another incident X-ray photon. If the first voltage comparator **301** has been deactivated, the controller **310** can activate it at any time before RST expires. If the controller **310** has been deactivated, it may be activated before RST expires.

FIG. **20** schematically shows a temporal change of the electric current flowing through the electrode (upper curve) caused by noise (e.g., dark current, background radiation, scattered X-rays, fluorescent X-rays, shared charges from adjacent pixels), and a corresponding temporal change of the voltage of the electrode (lower curve), in the system **121** operating in the way shown in FIG. **19**. At time t_0, the noise begins. If the noise is not large enough to cause the absolute value of the voltage to exceed the absolute value of V**1**, the controller **310** does not activate the second voltage comparator **302**. If the noise is large enough to cause the absolute value of the voltage to exceed the absolute value of V**1** at time t_1 as determined by the first voltage comparator **301**, the controller **310** starts the time delay TD**2** and the controller **310** may deactivate the first voltage comparator **301** at the beginning of TD**2**. During TD**2** (e.g., at expiration of TD**2**), the controller **310** activates the second voltage comparator **302**. The noise is very unlikely large enough to cause the absolute value of the voltage to exceed the absolute value of V**2** during TD**2**. Therefore, the controller **310** does not cause the number registered by the counter **320** to increase. At time t_e, the noise ends. At time t_h, the time delay TD**2** expires. The controller **310** may be configured to deactivate the second voltage comparator **302** at expiration of TD**2**. After TD**2** expires, the controller **310** connects the electrode to an electric ground for a reset period RST to allow charge carriers accumulated on the electrode as a result of the noise to flow to the ground and reset the voltage. Therefore, the system **121** may be very effective in noise rejection.

FIG. **21** schematically shows a temporal change of the electric current flowing through the electrode (upper curve) caused by charge carriers generated by a series of X-ray photons incident on the diode or the resistor, and a corresponding temporal change of the voltage of the electrode (lower curve), in the system **121** operating in the way shown in FIG. **19** with RST expires before t_e. The voltage curve caused by charge carriers generated by each incident X-ray photon is offset by the residue voltage before that photon. The absolute value of the residue voltage successively increases with each incident photon. When the absolute value of the residue voltage exceeds V**1** (see the dotted rectangle in FIG. **21**), the controller starts the time delay TD**2** and the controller **310** may deactivate the first voltage comparator **301** at the beginning of TD**2**. If no other X-ray photon incidence on the diode or the resistor during TD**2**, the controller connects the electrode to the electrical ground during the reset time period RST at the end of TD**2**, thereby resetting the residue voltage. The residue voltage thus does not cause an increase of the number registered by the counter **320**.

While various aspects and embodiments have been disclosed herein, other aspects and embodiments will be apparent to those skilled in the art. The various aspects and embodiments disclosed herein are for purposes of illustration and are not intended to be limiting, with the true scope and spirit being indicated by the following claims.

What is claimed is:

1. A method for making an apparatus suitable for detecting X-ray, the method comprising:

obtaining a wafer and a plurality of chips;

wherein each of the chips comprises an X-ray absorption layer comprising a first plurality of electrical contacts;

wherein the wafer has multiple dies and comprises an electronic layer comprising a second plurality of electrical contacts and an electronic system configured to process or interpret signals generated by X-ray photons incident on the X-ray absorption layer;

aligning the first plurality of electrical contacts to the second plurality of electrical contacts;

mounting the chips to the wafer such that the first plurality of electrical contacts are electrically connected to the second plurality of electrical contacts;

wherein at least one of the chips comprises a first transmission line electrically bridging at least some of the dies;

wherein the wafer comprises a second transmission line electrically bridging at least some of the chips;

wherein the second plurality of electrical contacts are configured to feed the signals to the electronic system.

2. The method of claim **1**, wherein the wafer has a first portion and a second portion, the first portion and the second portion separated by a gap in the wafer; wherein the first transmission line electrically bridges the first portion and the second portion across the gap.

3. The method of claim **1**, further comprising attaching the chips to a support wafer.

4. The method of claim **3**, wherein the chips are attached to the support wafer before the chips are mounted to the wafer.

5. The method of claim **3**, further comprising removing the support wafer.

6. The method of claim **5**, wherein removing the support wafer comprises grinding or etching the support wafer.

7. The method of claim **1**, further comprising encapsulating the chips in a matrix.

8. The method of claim **7**, further comprising exposing the first plurality of electrical contacts.

9. The method of claim **2**, further comprising encapsulating the first portion and the second portion in a matrix.

10. The method of claim **9**, further comprising exposing the second plurality of electrical contacts.

11. The method of claim **1**, wherein the electronic layer comprises vias extending to a surface opposite to the X-ray absorption layer.

12. The method of claim **11**, further comprising aligning the vias to contact pads on an interposer substrate, and bonding the wafer to the interposer substrate such that the vias are electrically connected to the contact pads.

13. The method of claim **12**, wherein the interposer substrate comprises transmission lines electrically connected to the contact pads and configured to route a signal on the contact pads to bonding pads on an edge of the interposer substrate.

14. The method of claim **13**, further comprising mounting the interposer substrate to a printed circuit board or positioning the interposer substrate side-by-side with a printed circuit board.

15. The method of claim **1**, wherein the electronic layer comprises a third plurality of electrical contacts configured to read output from the electronic system or to provide power or a reference voltage to the electronic system.

16. The method of claim **15**, wherein the X-ray absorption layer comprises a fourth plurality of electrical contacts configured to connect with the third electrical contacts when the chips are mounted to the wafer.

17. The method of claim **16**, wherein the X-ray absorption layer further comprises transmission lines configured to route a signal at the fourth plurality of electrical contacts to bonding pads on the X-ray absorption layer.

18. The method of claim **1**, wherein the wafer comprises a transmission line within at least one of the dies.

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