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(71) Applicant (for all designated States except US): **NXP B.V.**

[NL/NL]; NXP Semiconductors IP & L, High Tech Campus 60, NL-5656 AG Eindhoven (NL).

(72) Inventor; and

(75) Inventor/Applicant (for US only): **VAN DALEN, Rob**

[NL/NL]; c/o NXP Semiconductors, IP & L Department, 1109 McKay Drive, MS-41, San Jose, California 95131 (US).

(74) Agent: **WILLIAMSON, Paul**; c/o NXP Semiconductors,

IP & L Department, Betchworth House, 57-65 Station Road, Redhill Surrey RH1 1DL (GB).

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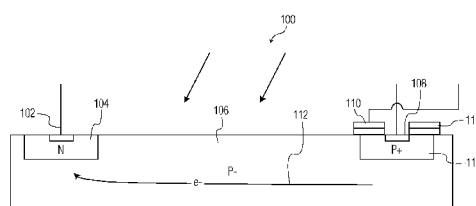


FIG. 1A

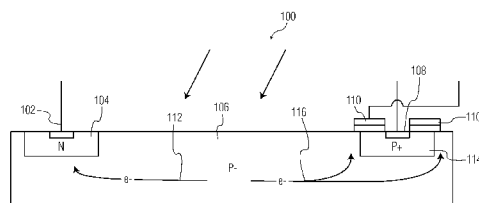


FIG. 1B

(57) Abstract: Various photon-detection devices, systems and methods are implemented. One such method is implemented for use imaging device having an integrated circuit die with an array that includes a plurality of pixels for collecting image data. The method is implemented in a single pixel. An electrical signal is produced in a photo-sensitive layer in response to stimulus from photons. A portion of the produced electrical signal is received at a signal contact. A voltage is applied to a gate of a controllable transistor located in the single pixel. The applied voltage forms a conductive channel in a non- conductive layer that is distinct and different from the photo-sensitive layer, the non- conductive layer otherwise electrically isolating the drain from the photo-sensitive layer with respect to the produced electrical signal. The photo-sensitive layer is used as a source of the controllable transistor. The channel is conductive with respect to the produced electrical signal.



WO 2009/093221 A2

81057817WO01

1

ARRANGEMENT AND APPROACHES FOR ADAPTIVE GAIN PHOTO DETECTORS

Photo-detectors are used in a variety of applications including various imaging
5 systems. Photo-detectors generally include a photo-sensitive portion that generates
electrical current or charge in response to stimulus by photons. A specific example of
such a photo-detector is a photo-diode. Electron hole pairs are generated in the photo-
sensitive portion through interactions with photons. The electron hole pairs result in the
generation of an electrical signal/current. This generated signal/electrical current can be
10 relatively small. In an array of detectors, each detector functioning as a pixel, the small
signal/current may be insufficient to transmit from the detector to a receiving circuit.
Thus, many photo-sensitive devices implement an amplification stage at the pixel level.
In such devices, the amplification circuit is located proximate to each photo-detector,
such as being located on the same integrated-circuit (IC) die. In certain instances, an
15 amplification circuit is implemented for each pixel.

Certain applications benefit from the ability to operate in different modes of
sensitivity. Generally, the amplification stage has a given operating range. The
resolution of the pixel, with regard to the intensity of the received photons, can be
increased by matching the maximum intensity of the received photons with the operating
20 range of the amplification stage. Some imagers with multiple selectable gain settings
(e.g., multi-mode photo-detectors) operate using switched capacitor networks. The
capacitors are selectively enabled to change the value of the signal received by the
amplification stage relative to the signal generated by the photo-diode. This effectively
changes the gain provided by the pixel. Such capacitors may require a significant die
25 area to implement.

While these approaches have been used with success, improvement in multi-mode
photo-detector technology remains highly desirable, particularly as photo-detectors are
decreased in size and as image quality is increased. In this regard, photo-detector size
and other issues continue to present challenges to the implementation and generation of
30 photo-detectors, particularly at the pixel level.

81057817WO01

2

Various aspects of the present invention are directed to arrangements for and methods of processing image data in a manner that addresses and overcomes the above-mentioned issues and other issues as directly and indirectly addressed in the detailed description that follows.

Consistent with an example embodiment of the present invention, an integrated circuit die is implemented for use in an imaging device. The imaging device has an array of pixels for collecting image data and located on an integrated circuit die. At least one pixel has a photo-sensitive layer that produces an electrical signal in response to stimulus from photons. A signal contact electrically connects to the photo-sensitive layer to receive a portion of the produced electrical signal. A controllable transistor in the pixel includes a drain a source and a gate. The source includes the photo-sensitive layer. A semi-conductive layer that is distinct and different from the photo-sensitive layer has a first state and a second state. In the first state the semi-conductive layer electrically isolates the drain from the source with respect to the produced electrical signal. In the second state a conductive channel is formed in the semi-conductive layer. The channel being conductive with respect to the produced electrical signal and extending from the drain to the source to form an electrical connection therebetween. The gate is electrically coupled to the semi-conductive layer such that, in response to voltage applied to the gate contact the semi-conductive layer switches between the first state and the second state.

Consistent with another example embodiment of the present invention, a method is implemented for use in an imaging device having an array of pixels for collecting image data and located on a single IC die. The method is implemented in a single pixel. An electrical signal is produced in a photo-sensitive layer in response to stimulus from photons. A portion of the produced electrical signal is received at a signal contact. A voltage is applied to a gate of a controllable transistor located in the single pixel. The applied voltage forms a conductive channel in an otherwise non-conductive layer that is distinct and different from the photo-sensitive layer. The non-conductive layer isolates the drain from a source that includes the photo-sensitive layer. The electrical isolation is relative to the produced electrical signal. The conductive channel forms an electrical

81057817WO01

3

connection between as a source and drain. The channel being conductive with respect to the produced electrical signal.

Consistent with another example embodiment of the present invention, a method is implemented for detecting photons using an integrated-circuit die. The method includes the production of an electrical signal in response to photon-based stimulus of a photo-sensitive layer. A portion of the produced electrical signal is received at a signal contact. A voltage is applied to a gate contact that is electrically coupled to a non-conductive layer. The voltage affects a signal strength of the received portion of the produced electrical signal by forming a conductive channel in the non-conductive layer.

The conductive channel extends between a drain contact and the photo-sensitive layer.

Consistent with another example embodiment of the present invention, a system is implemented for detecting photons using an integrated-circuit die. The system includes means for producing an electrical signal in response to photon-based stimulus of a photo-sensitive layer. A portion of the produced electrical signal is received at a signal contact.

Means are implemented for applying a voltage to a gate contact that is electrically coupled to a non-conductive layer. The voltage affects a signal strength of the received portion of the produced electrical signal by forming a conductive channel in the non-conductive layer. The conductive channel extends between a drain contact and the photo-sensitive layer.

Consistent with another example embodiment of the present invention, an integrated die is implemented for use in a device that detects photons. The integrated-circuit die has a photo-sensitive layer that produces an electrical signal in response to stimulus from photons. A signal contact electrically couples to the photo-sensitive layer to receive a portion of the produced electrical signal. A controllable element includes a non-conductive layer adjacent to the photo-sensitive layer, a drain contact electrically coupled to the non-conductive layer and a gate contact electrically coupled to the non-conductive layer such that, in response to voltage applied to the gate contact, a conductive channel is formed in the non-conductive layer. The conductive channel extends between the drain contact and the photo-sensitive layer, thereby affecting a signal strength of the portion of the produced electrical signal.

81057817WO01

4

The above summary of the present invention is not intended to describe each embodiment or every implementation of the present invention. Other aspects of the invention will become apparent and appreciated by referring to the following detailed description and claims taken in conjunction with the accompanying drawings.

5 The invention may be more completely understood in consideration of the following detailed description of various embodiments of the invention in connection with the accompanying drawings, in which:

FIG. 1A depicts a view of an inactive controllable element that is implemented to affect the sensitivity of a photo-detector, according to an example embodiment of the
10 present invention;

FIG. 1B depicts a view of an active controllable element that is implemented to affect the sensitivity of a photo-detector, according to an example embodiment of the present invention;

FIG. 2 depicts one example of an circuit that is implemented according to an
15 example embodiment of the present invention;

FIG. 3 depicts a top-down view of a controllable element consistent with an embodiment of the present invention;

FIG. 4A depicts a cross-sectional view of FIG. 3, as consistent with an embodiment of the present invention;

20 FIG. 4B depicts another cross-sectional view of FIG. 3, as consistent with an embodiment of the present invention;

FIG. 4C depicts another cross-sectional view of FIG. 3, as consistent with an embodiment of the present invention; and

25 FIG. 5 shows a single pixel with multiple controllable elements, according to an example embodiment of the present invention.

While the invention is amenable to various modifications and alternative forms, specifics thereof have been shown by way of example in the drawings and will be described in detail. It should be understood, however, that the intention is not to limit the invention to the particular embodiments described. On the contrary, the intention is to cover all
30 modifications, equivalents, and alternatives falling within the scope of the invention as defined by the appended claims.

81057817WO01

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The present invention is believed to be applicable to a variety of arrangements and approaches for variable/adaptive gain photo-detectors. While the present invention is not necessarily limited to such applications, an appreciation of various aspects of the invention is best gained through a discussion of examples in such an environment.

In certain applications it is desirable to image over a wide range of incident photon rates. One such application is X-ray detectors for medical applications. Such detectors may be expected to image across extremely large X-ray dose ranges. The dosage range can range from 5nGy to 25mGy. This corresponds to a dynamic range of 22 bits, which poses a

potential problem for the analog-to-digital conversion as it may be prohibitively expensive to implement an analog-to-digital converter (ADC) that is able to directly handle such a large dynamic range. One embodiment of the present invention provides a pixel-level gain control that can be used to facilitate applications implementing such large resolution ranges. In this embodiment a controllable element is built into the photo-detector. When disabled, a pixel-level gain stage detects substantially all of the photo-generated carriers. When enabled, the controllable element receives a portion of photo-generated carriers, thereby reducing the number of carriers that are detected by the gain stage. Accordingly, the ratio between the incident photon rate and the output of the gain stage can be effectively reduced by enabling the controllable element.

The skilled artisan would recognize that many of the systems, methods and circuits described herein would be applicable to photo-detection applications outside of X-ray imaging. Particularly, many of the embodiments discussed herein may be found useful for a variety of applications including, for example, those applications that would benefit from dynamic adjustment of pixel-level sensitivity.

FIGs. 1A and 1B show one embodiment of the present invention in which a controllable element is implemented to affect the sensitivity of a photo-detector. Photo-responsive layer 106 generates electron-hole pairs in response to incident photons 100. This produces a current shown by electron drift 112. Contact/terminal 102 is separated from photo-responsive layer 106 by layer 104. In a specific embodiment, layer 104 and photo-responsive layer 106 form a PN or PIN junction that operates as a photo-diode. In one instance, this photo-diode is reversed biased to function in photoconductive mode. In

81057817WO01

6

photoconductive mode, the electron drift 112 represents a reverse-bias current flow that can be used to measure the number/intensity of incident photons 100.

FIG. 1A and 1B each show a controllable element that includes a contact/terminal 108. Contact 108 is insulated from photo-responsive layer 106 by a non-conductive layer 114. Non-conductive layer 114 is non-conductive with respect to current shown by electron drift 112. Unless otherwise stated, the term non-conductive, as used herein, denotes conductivity that is with respect to the current generated in the photosensitive layer in response to photon stimulation. Gate 110 is responsive to an input-control signal. Specifically, gate 110 enables or disables the controllable element in response to an applied voltage. When the controllable element is disabled, contact 108 is not electrically coupled/connected to photo-responsive layer 106. This disabled condition is shown by FIG. 1A, where substantially all of the generated current (i.e., electron drift 112) is received by contact 102. Gate 110 can include both a gate oxide portion and a polysilicon gate contact. The gate oxide can prevent current from flowing from the underlying silicon to the gate contact.

When the controllable element is enabled, a conductive channel is formed in the non-conductive layer 114. Specifically, a voltage applied to gate 110 results in the formation of the conductive channel. This enabled condition is shown by FIG. 1B. Due to the conductive channel, at least a portion of the generated current is received by contact 108. Accordingly, the electron drift is split between contacts 102 and 108 as shown by electron drift 112 and 116, respectively. Generally speaking, the number of electron hole pairs generated in photo-responsive layer 106 is relatively independent of whether the controllable element is enabled. Accordingly, enabling gate 110 results in a reduction in the amount of current seen at contact 102 that is proportional to the amount of current seen at contact 108. The controllable element can be implemented on the same die as the photo-responsive layer 106, and more specifically, within the responsive layer 106.

In a specific embodiment of the present invention, non-conductive layer 114 is a layer that is doped to a higher concentration than the doping concentration of photo-responsive layer 106. Thus, non-conductive layer 114 has a higher concentration of majority carriers that inhibits the flow of carriers forming the current seen at contact 102.

81057817WO01

7

Thus, the non-conductive layer 114 and the photo-responsive layer 106 can each be either P or N doped, with the non-conductive layer 114 forming a more heavily doped well of the same doping type as the photo-responsive layer 106.

A number of variations are possible with regards to the basic photo-detector design shown by FIG. 1. For instance, contact 102 layer 104 can function as a gated diode with the addition of a gate contact that spans from contact 102 to the PN junction. In another instance, various doping layers can be implemented to control the current drift in the photo-responsive layer 106. Such layers include, but are not limited to, a surface layer located at the upper portion of photo-responsive layer 106, a sidewall layer separating the pixel from other pixels or circuitry or an implant layer located between a portion of photo-responsive layer 106 and the substrate. In a particular instance, such layers can be implemented by more heavily doping the layers. Thus, if photo-responsive layer 106 is lightly N-doped, these layers can be implemented using increased N-doping concentrations. In one instance, the layers can be used to affect the responsiveness of the photo detector to specific wavelengths of photons.

According to one embodiment of the present invention involves an ADC conversion of the electrical signal produced by the photo detector. For example, a photon-counting detector or optical photo-detector estimates the incident photon rate occurring during sample intervals. Specifically, the photo-detector generates a current that is proportional to the photon rate. A circuit generates a voltage level that is proportional to the number of photons collected by the photo-detector during the sample intervals. In a specific instance, the proportional voltage is generated using an integrating circuit, which can be implemented using one or more capacitors. The integrating circuit charges or discharges the capacitors using the photo-detector current. The charge on the capacitor is removed during a sample stage and can be reset to a beginning value (e.g., a known voltage) at the end of the sample stage. In a particular embodiment, a feedback mechanism provides a sensitivity control signal to increase or decrease the effective range of the photo-detector. This control signal is coupled/connected to the gate of the photo-detector to enable or disable the second terminal.

FIG. 2 depicts one example of a pixel having an amplifier circuit that can be used with such an ADC circuit and that is consistent with an example embodiment of the present

81057817WO01

8

invention. Photo-diode 202 operates in photoconductive mode (i.e., is reversed biased). As photo-diode 202 is stimulated by photons, free electron-hole pairs are generated. These electron-hole pairs contribute to a reverse-biased flow of current. Reset gate 202 operates to set the voltage level at the cathode of photo-diode 202 to a known level.

- 5 When reset gate 202 is released, the voltage level drops at a rate that is consistent with the level of photons stimulating photo-diode 202. This results in a corresponding change in the voltage seen on the gate of transistor 210. This change in gate voltage in combination with the current source 212 produces a voltage output 214 that is proportional to the level of photons stimulating photo-diode 206. In a specific instance,
10 output 214 is converted to a digital value using an ADC.

The dotted line 200 represents the photo-sensitive area of the pixel. Within 200 is both controllable element/transistor 208 and photo-diode 202. Controllable element is enabled in response to a voltage seen at gate 204. This voltage can be responsive to a desired sensitivity level. Specifically, when less sensitivity is desired the transistor 208
15 can be activated. This allows a portion of the current generated by photo-diode 206 to flow to node 216. Due to the location of the controllable element within the photo-responsive layer of the photo-diode 206, the amount of photo-generated current seen on the gate of transistor 210 is reduced. Node 216 can be connected to various voltage sources or to ground.

- 20 Although not shown, the circuit of FIG. 2 can optionally be implemented with additional gain control. A specific example of such gain control includes the use of one or more switched capacitors. Conceptually, the switched capacitors can be connected in much the same manner as transistor 210. Thus, multiple adaptive-gain control circuits techniques can be used while still being consistent with various embodiments of the
25 present invention.

FIG. 3 shows a top-down view of a controllable element 300 consistent with an embodiment of the present invention. Controllable element 300 includes vias 306 and 316, which are electrically coupled to metal lines 310 and 312, respectively. Via(s) 306 electrically connect metal line 310 to contact/terminal area 308. Nonconductive layer
30 314 electrically isolates terminal 308 from the photo-sensitive layer. Via(s) 316 electrically connect metal line 312 with gate layer 315. A voltage applied to gate layer

81057817WO01

9

315 (i.e., from metal line 312) creates a conductive channel in nonconductive layer 314 to allow current to flow between terminal 308 and the photo-sensitive layer.

Dotted line 302 represents the point at which the cross-sections depicted in FIG. 4A and FIG. 4B are taken. Dotted line 304 represents the point at which the cross-section

5 depicted in FIG. 4C is taken.

FIG. 4A shows a cross-sectional view of FIG. 3 taken at dotted line 302, as consistent with an embodiment of the present invention. Layer 404 is the photo-sensitive layer. Layer 406 is the substrate layer. Layer 402 is a buried implant layer. In a specific embodiment, substrate layer 406 is a P+ doped layer (e.g., doped to around $1 \times 10^{17} \text{ cm}^{-3}$ to $1 \times 10^{20} \text{ cm}^{-3}$), photosensitive layer 404 is a P- doped layer (e.g., doped to around $1 \times 10^{14} \text{ cm}^{-3}$ to $1 \times 10^{16} \text{ cm}^{-3}$), and buried implant layer 402 is a P+ doped layer (e.g., doped to around $1 \times 10^{16} \text{ cm}^{-3}$ to $1 \times 10^{18} \text{ cm}^{-3}$). These doping concentrations are merely illustrative of one embodiment and various other doping profiles are possible. For example, embodiments of the invention can be implemented using N doped layers in place of the P doped layers.

15 FIG. 4B shows a cross-sectional view of FIG. 3 taken at dotted line 302, as consistent with an embodiment of the present invention. In one embodiment, layer 404 is a P-epi layer formed on a P+ substrate 406. Layer 402 represents an optional buried layer (e.g., a P-well) for tuning the wavelength response of the photo-sensitive area. For the embodiment described, this buried layer will be formed by means of a highly doped P+ layer, which will act as a barrier for photo-generated electrons and thus limit the collection depth of the photo-sensitive area. Such an approach, sometimes used in combination with similar P+ sidewall barriers (layer 408), can be particularly useful to suppress the response to infrared (IR) radiation or direct X-ray events.

25 FIG. 4C shows a cross-sectional view of FIG. 3 taken at dotted line 304, as consistent with an embodiment of the present invention. Layer 404 is shown twice, but only because it surrounds layer 402. In a specific embodiment, the non-conductive layer 314 is a P-well that inhibits electron flow to the N+ region 308. With the gate in the on-state, the surface that is between p+ top layer and n+ contact area, and that is overlapped with the gate poly, becomes inverted (i.e., features an conductive-electron channel), creating an 'escape path' for photo-generated electrons in the p epi layer.

81057817WO01

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FIG. 5 shows a photo-detector pixel with multiple controllable elements, according to an example embodiment of the present invention. Photo-detector pixel 500 includes four different controllable elements depicted by 502, 504, 506 and 508. A combination of one or more of these elements can be enabled to provide different gain levels relative to the output provided at contact 510.

While FIG. 5 shows the controllable elements arranged at the corners of the IC die 500, a number of different placements are possible. For instance, the elements can be placed at different distances from the contact 510, thereby affecting the output of contact 510 differently with respect to their distance from contact 510. Other examples include concentric rings surrounding the contact 510, staggered locations and gate elements of different sizes and shapes.

One embodiment of the present invention involves a calibration of an IC die with respect to the controllable element being enabled or disabled. A photon intensity having a known value can be used to measure the differences between gains seen when the controllable element is enabled and disabled, respectively. The results of the measurements can be used to adjust the intensity values for the pixel. In one instance, the calibration can be performed during the design phase and applied to subsequent devices. In another instance, the calibration can be implemented for each manufacturing run or wafer, so as to account for manufacturing variance. In yet another instance, the calibration can be performed for each pixel.

The various embodiments described above and shown in the figures are provided by way of illustration only and should not be construed to limit the invention. Based on the above discussion and illustrations, those skilled in the art will readily recognize that various modifications and changes may be made to the present invention without strictly following the exemplary embodiments and applications illustrated and described herein.

81057817WO01

11

Such modifications and changes do not depart from the true scope of the present invention that is set forth in the following claims.

81057817WO01

12

What is claimed is:

1. For use in an imaging device having an integrated circuit die that includes a plurality of pixels for collecting image data, a single pixel comprising:
 - a photo-sensitive layer (106) that produces an electrical signal (112, 116)) in response to stimulus from photons;
 - a signal contact (102, 104) electrically connected to the photo-sensitive layer to receive a portion of the produced electrical signal; and
 - a controllable transistor in the photo-sensitive layer (106) including;
 - a drain (108);
 - a source (106) that includes the photo-sensitive layer;
 - a semi-conductive layer (114) that is distinct and different from the photo-sensitive layer and that has a first state and a second state, wherein
 - in the first state the semi-conductive layer (114) electrically isolates the drain from the source with respect to the produced electrical signal (112, 116), and
 - in the second state a conductive channel is formed in the semi-conductive layer, the channel being conductive with respect to the portion of the produced electrical signal and extending from the drain (108) to the source (106) to form an electrical connection therebetween; and
 - a gate contact (110) electrically coupled to the semi-conductive layer (114) such that, in response to voltage applied to the gate contact (110) the semi-conductive layer (114) switches between the first state and the second state.
2. The pixel of claim 1, wherein the signal contact and the photo-sensitive layer form a PN junction.
3. The pixel of claim 1, wherein the semi-conductive layer is doped to a higher concentration than a doping concentration of the photo-sensitive layer.
4. The pixel of claim 1, wherein the gate contact is separated from the semi-conductive layer by an electrical insulator layer.

81057817WO01

13

5. The pixel of claim 1, wherein the signal contact is either N or P doped and the photo-sensitive layer is the other of N or P doped.
6. The pixel of claim 1, further including one or more additional controllable elements located within the photo-sensitive layer and receiving a portion of the produced electrical signal responsive to respective signals applied to a respective gate contact.
7. The pixel of claim 1, further including a capacitor that can be selectively coupled to the signal contact to change an optical to electrical gain of the photo-detector.
8. The pixel of claim 1, further including a circuit electrically coupled to the signal contact to provide an output that represents an integration of the produced electrical signal seen at the contact.
9. The pixel of claim 1, further including an implant layer that is more heavily doped than the photo-sensitive layer, the implant layer being arranged to contain the produced electrical signal.
10. For use in an imaging device having an integrated circuit die with an array that includes a plurality of pixels for collecting image data, a method implemented in a single pixel and comprising:
 - producing an electrical signal (112, 116) in a photo-sensitive layer (106) in response to stimulus from photons;
 - receiving a portion of the produced electrical signal (112) at a signal contact (102, 104); and
 - applying a voltage to a gate (110) of a controllable transistor located in the photo-sensitive layer (106), wherein the applied voltage forms a conductive channel in an otherwise non-conductive layer (114) that is distinct and different from the photo-sensitive layer (106), the non-conductive layer (114) otherwise electrically isolating a drain (108) from a source (106) that includes the photo-sensitive layer (106), the isolation relative to the portion of the produced electrical signal (112, 116).
11. The method of claim 10, further including the step of generating an image using the received portion of the produced electrical signal.

81057817WO01

14

12. The method of claim 10, further including the step of determining a desired sensitivity for the single pixel, wherein the applied voltage is responsive to the step of determining the desired sensitivity.

13. The method of claim 10, further including the step of generating an image using respective electrical signals from the plurality of pixels, wherein each electrical signal represents data for generating the image.

14. The method of claim 10, further including the step of converting the received portion of the produced electrical signal to a digital value that represents the signal strength.

15. The method of claim 10, further including the step of applying a control signal to a gate of a switchable capacitor circuit to affect a gain with respect to an output voltage and the produced electrical current.

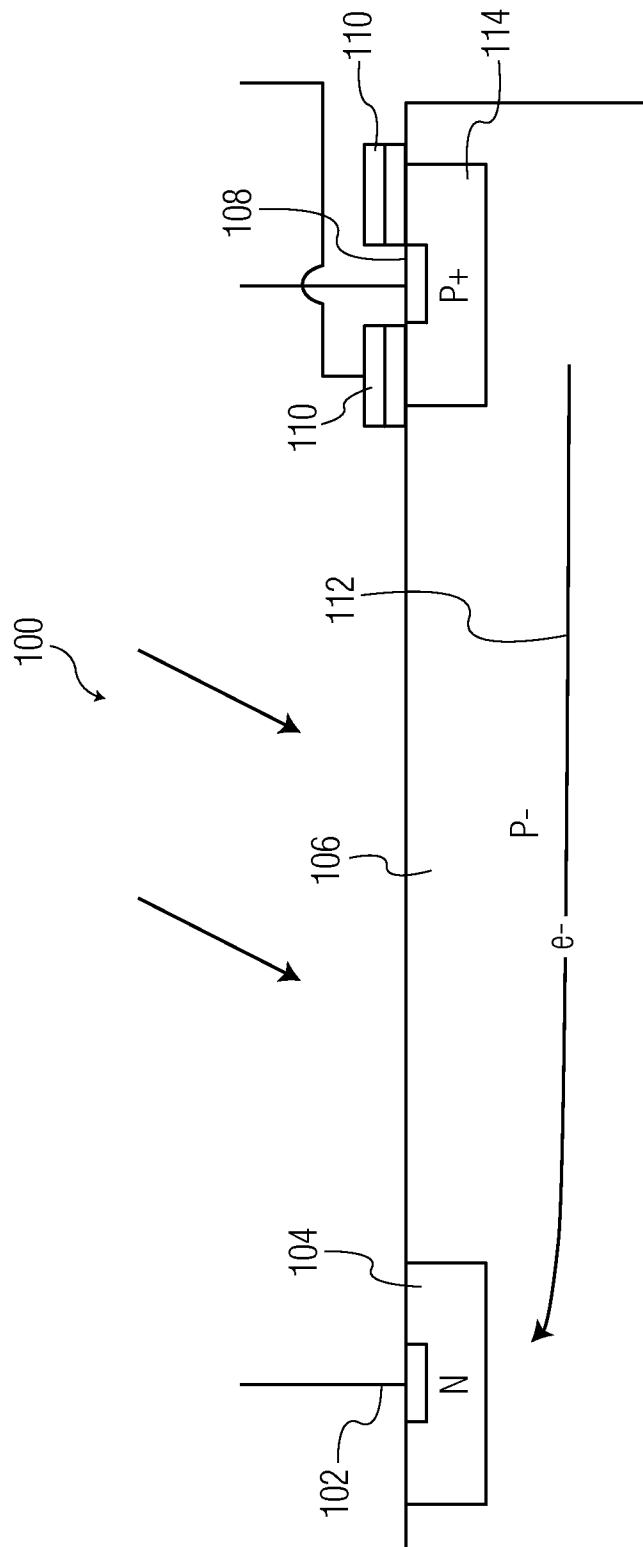


FIG. 1A

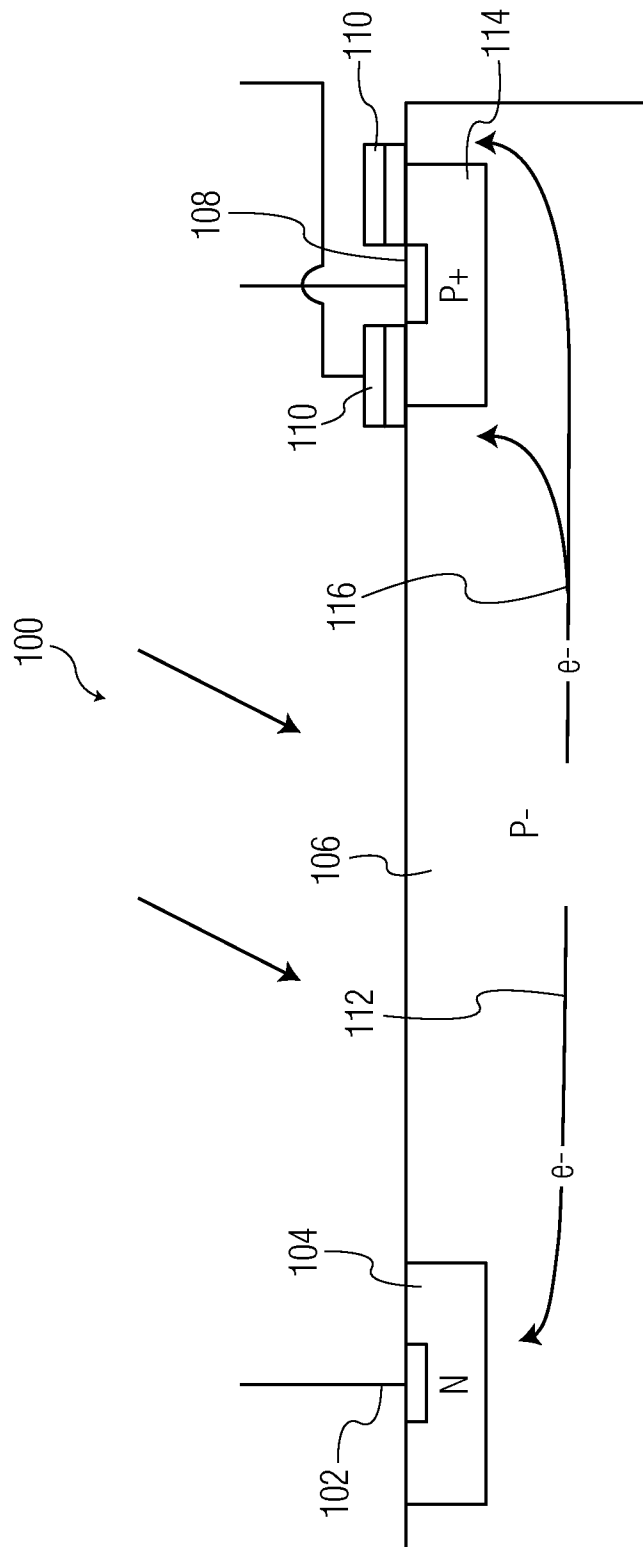


FIG. 1B

3/7

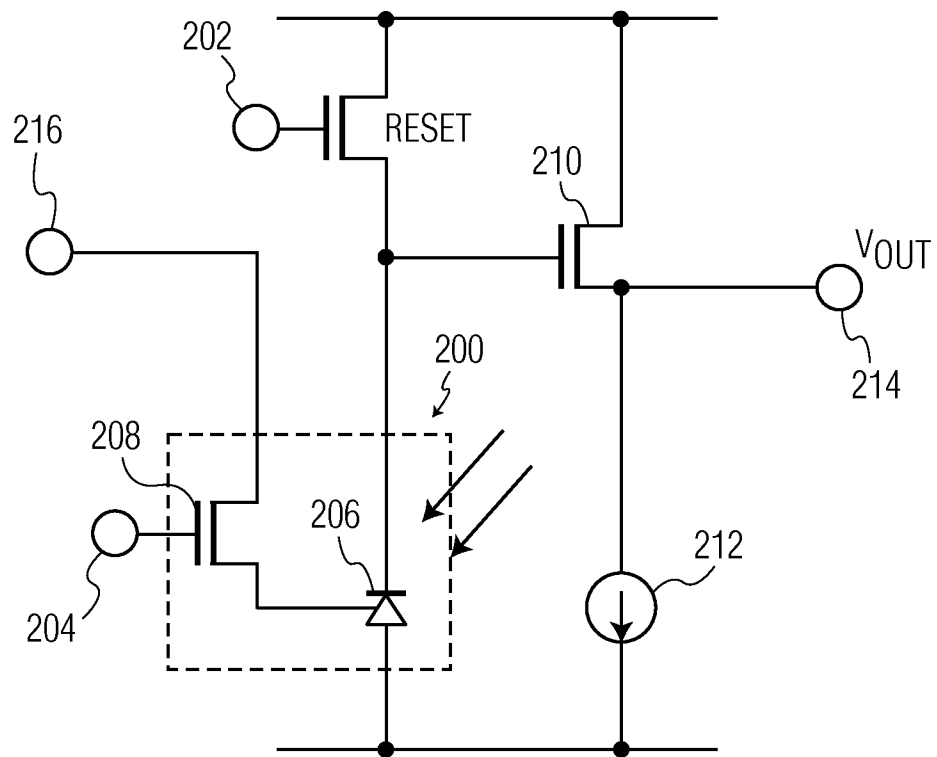


FIG. 2

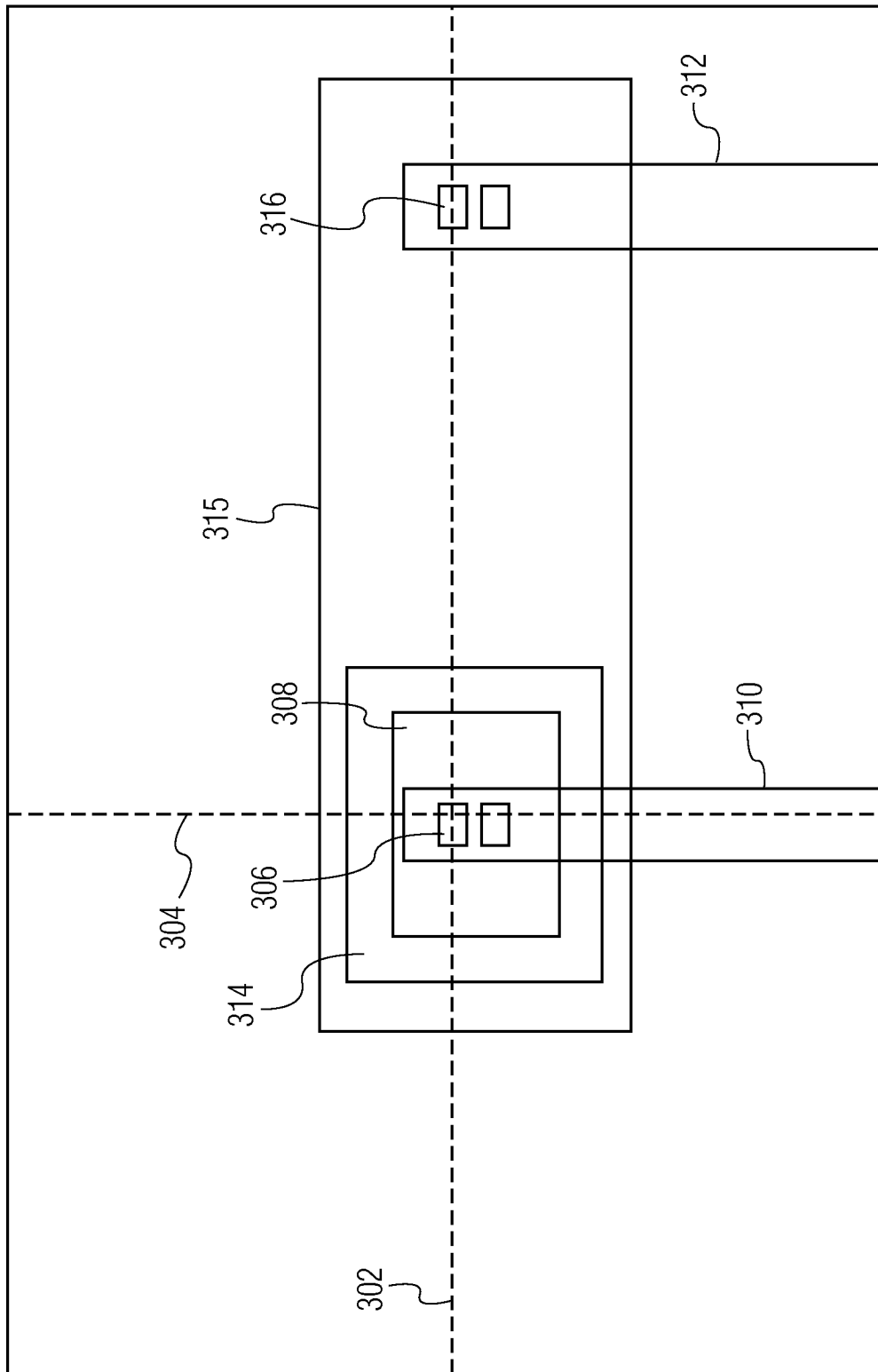
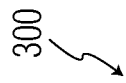


FIG. 3

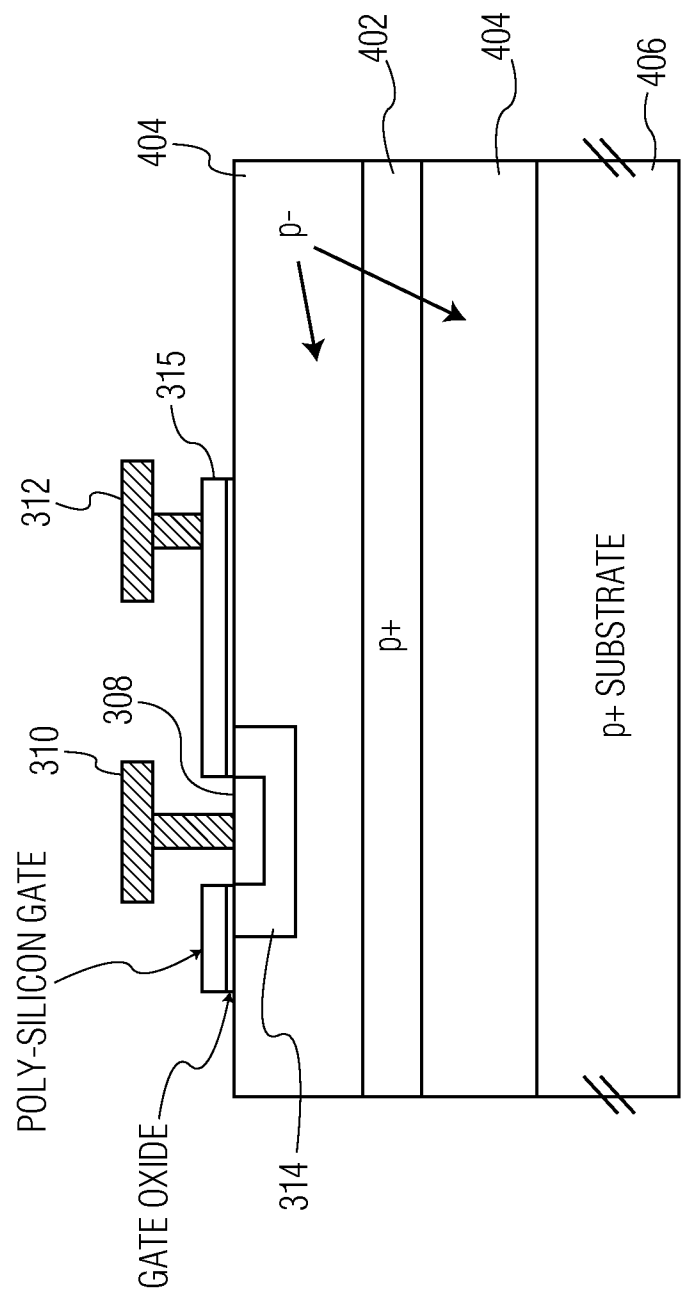


FIG. 4A

6/7

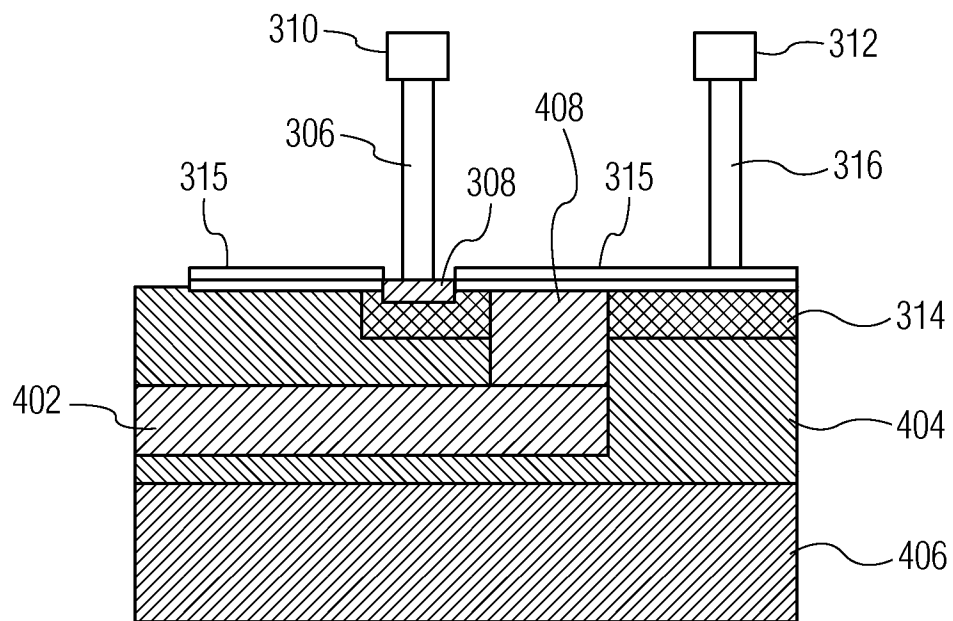


FIG. 4B

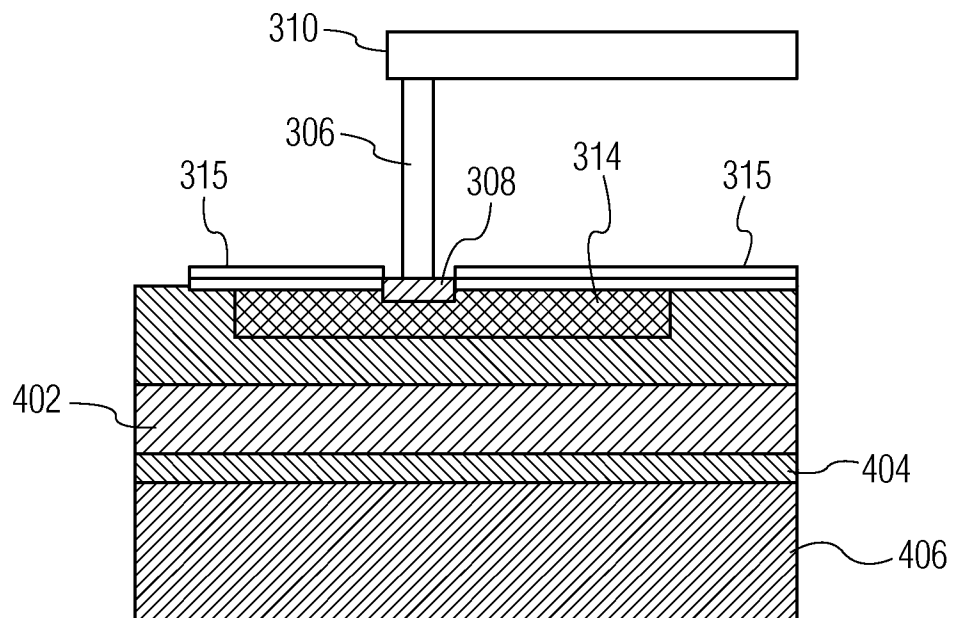


FIG. 4C

7/7

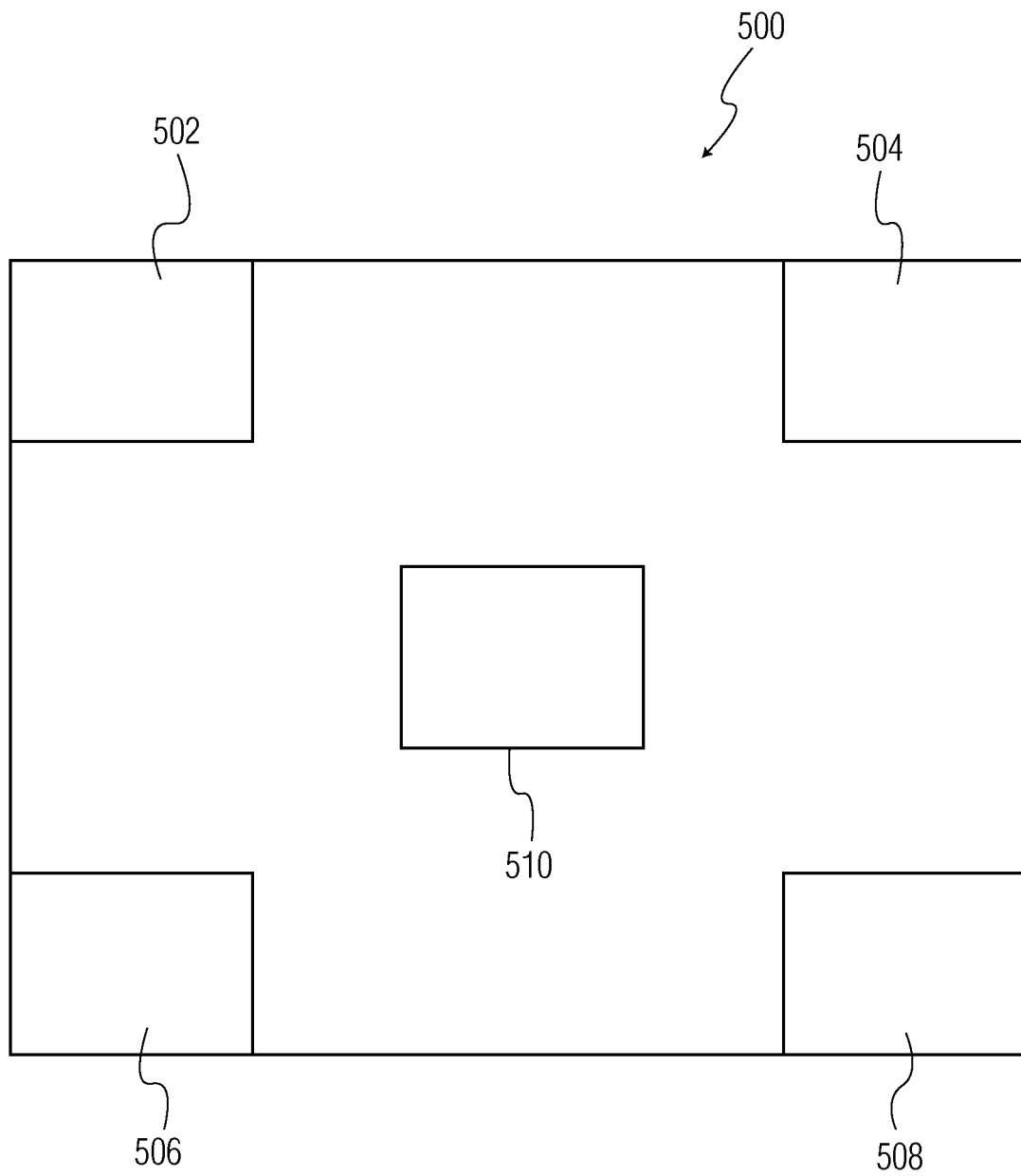


FIG. 5