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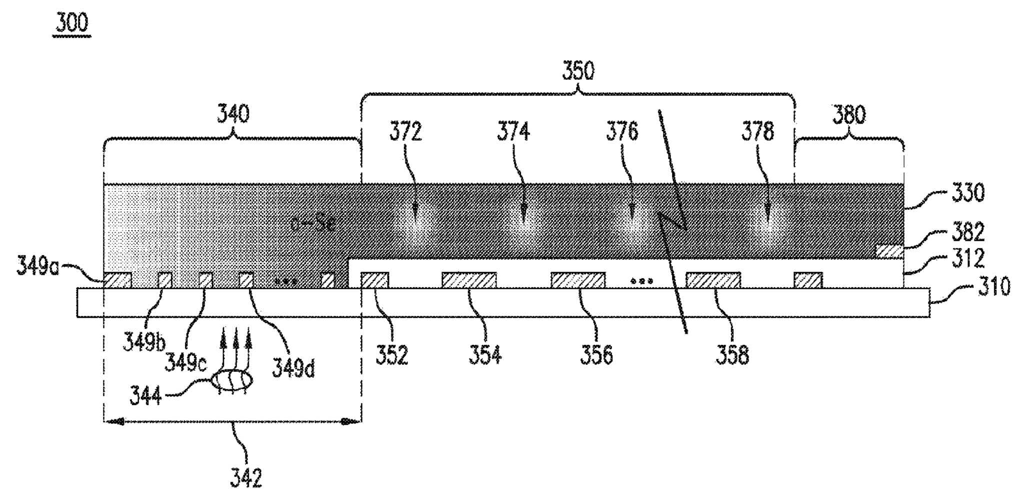

(57) Abrégé/Abstract:
Provided is a field shaping multi-well photomultiplier and method for fabrication thereof. The photomultiplier includes a field-shaping multi-well avalanche detector, including a lower insulator, an a-Se photoconductive layer and an upper insulator. The a-Se photoconductive layer is positioned between the lower insulator and the upper insulator. A light interaction region, an avalanche region, and a collection region are provided along a length of the photomultiplier, and the light interaction region and the collection region are positioned on opposite sides of the avalanche region.

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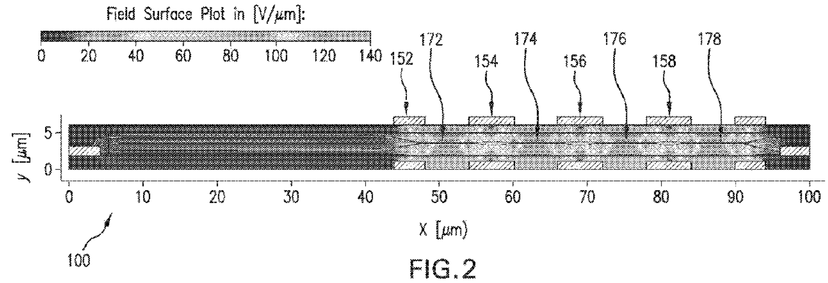

FIG.2

(57) Abstract: Provided is a field shaping multi-well photomultiplier and method for fabrication thereof. The photomultiplier includes a field-shaping multi-well avalanche detector, including a lower insulator, an a-Se photoconductive layer and an upper insulator. The a-Se photoconductive layer is positioned between the lower insulator and the upper insulator. A light interaction region, an avalanche region, and a collection region are provided along a length of the photomultiplier, and the light interaction region and the collection region are positioned on opposite sides of the avalanche region.

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SELENIUM PHOTOMULTIPLIER AND METHOD FOR FABRICATION THEREOF

BACKGROUND OF THE INVENTION

1. Field of the Invention:

The present invention relates generally to the field of solid-state radiation imaging detectors and, in particular, to amorphous selenium radiation detectors having a field-shaping multi-well detector structure.

2. Description of the Related Art:

The field of nuclear medicine and its applications in diagnostic imaging is growing fast and the use of solid-state photomultipliers, in the form of single element or pixel array detectors, have been under investigation to yield performance characteristics similar to a conventional photomultiplier tube (PMT). Advantages of solid-state technology are ruggedness, compact size, and insensitivity to magnetic fields. Thus far, silicon photomultipliers (SiPMs) which are built from an avalanche photodiode (APD) array seem to be the only candidate for the replacement of PMTs in positron emission tomography (PET) and single-photon emission computed tomography (SPECT) imaging and are rapidly developing. However, in contrast to PMTs, SiPMs do not operate in a linear mode and suffer from poor photon detection efficiency, small area, high cost, poor uniformity, and low yield.

To achieve avalanche gain (g_{av}) similar to a PMT of approximately 10^6, SiPMs are operated above breakdown in non-linear Geiger-mode which results in optical crosstalk. For

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high gain APDs which are linear-mode devices, the avalanche multiplication process due to impact ionization is stochastic and produces excess noise.

Fluctuations in the avalanche gain become progressively worse as the multiplication factor (M) is increased in APDs by raising the electric field (F). The slope of M versus F is a strong function of the ratio of the two carriers' ionization rates (k), where $1 \leq k < 0$ given that the ideal situation of single-carrier multiplication is seldom if ever the case in practical semiconductor materials, and that both electrons and holes can have impact ionizations. [1] The high k-value in crystalline silicon contributes to the uniformity and yield issues of APDs and SiPMs. Amorphous selenium (a-Se), which was previously developed for photocopying machines, is the only exception to this criterion.

a-Se is readily produced uniformly over large area at substantially lower cost compared to crystalline solids, and a-Se is the only amorphous material that produces avalanche at high fields. A key feature of this impact ionization process is that only holes become hot carriers and undergo avalanche multiplication. Consequently, avalanche selenium devices are linear-mode devices with a very low k value. Commercially, avalanche gain in a-Se enabled the development of the first optical camera with more sensitivity than human vision and, for example, capable of capturing astronomical phenomena such as auroras and solar eclipses. [2] a-Se has ~90% detection efficiency in the blue wavelength which makes it ideal to be coupled to blue-emitting scintillators for high-energy radiation detection. a-Se is a room-temperature semiconductor with wide band gap and ultra-low leakage current even at high fields.

Limitations of direct conversion a-Se FPDs include degradation of low-dose imaging performance due to electronic noise since the energy required to generate an electron-hole pair in a-Se is 50 eV at 10 V/micron. Although other photoconductive materials with higher conversion have been investigated, direct conversion a-Se FPDs remain far from commercialization due to charge trapping and manufacturing issues. Improved conversion of a-Se is possible by increasing the electric field above 30 V/micron, i.e., 30,000 V on a 1000 micron layer. However, this electric field increase is extremely challenging for reliable detector construction and operation, and is impractical.

Amorphous solids, i.e., non-crystalline solids with disorder, have been ruled out as viable radiation imaging detectors in a photon-counting mode because of low temporal resolution due to low carrier mobility and transit-time limited pulse response, and low conversion gain of high energy radiation to electric charge. A direct conversion a-Se layer with separate absorption and avalanche region has been suggested, but significant obstacles prevent practical implementation of a direct conversion a-Se layer with separate absorption and avalanche regions.

Unipolar solid-state detectors with a Frisch grid have been proposed. However, such detector structures are not practical for direct conversion avalanche gain because the highest electric field in the well develops at the interface between the semiconductor and the pixel electrode, resulting in a high dark current due to large charge injection and potentially irreversible damage to the detector.

A unipolar time-differential (UTD) solid-state detector has been fabricated using a high granularity micro pattern multi-well structure, i.e., a multi-well solid-state detector (MWSD). Also proposed are vertical detector structures based on UTD charge sensing and avalanche multiplication gain, i.e., a field-shaping multi-well avalanche detector (SWAD) and the nano-electrode multi-well high-gain avalanche rushing photodetector (NEW-HARP) [5-6].

SUMMARY OF THE INVENTION

Provided herein is a multi-well selenium detector and a method for the fabrication of same that overcomes the shortcomings of conventional systems, which improves signal rise time set by the spreading of a photo-induced carrier packet.

Accordingly, aspects of the present invention address the above problems and disadvantages and provide the advantages described below. An aspect of the present invention provides a single-carrier solid-state photomultiplier device structure that uses amorphous selenium (a-Se) as the photoconductive material with indirect x-ray and gamma-ray detection capability when coupled to scintillating crystals.

An aspect of the present disclosure provides a photomultiplier with a field-shaping multi-well avalanche detector, comprising a lower insulator; an a-Se photoconductive layer; and an upper insulator. The a-Se photoconductive layer is between the lower insulator and the upper insulator. A light interaction region, an avalanche region, and a collection region are provided along a length of the photomultiplier, and the light interaction region and the collection region are positioned on opposite sides of the avalanche region.

Another aspect of the present disclosure provides a photomultiplier with a field-shaping multi-well avalanche detector, comprising an insulator, a-Se photoconductive layer adjacent to the insulator, a light interaction region, an avalanche region and a collection region. The light interaction region, the avalanche region, and the collection region are provided along a length of the photomultiplier, and the light interaction region and the collection region are positioned on opposite sides of the avalanche region.

Another aspect of the present disclosure provides a photomultiplier with a field-shaping multi-well avalanche detector, comprising: an insulator; a-Se photoconductive layer adjacent to the insulator; a light interaction region; an avalanche region; a collection region; a plurality of high voltage dividers positioned in the light interaction region; and a collector positioned at a distal end of the collection region, wherein the light interaction region, the avalanche region, and the collection region are provided along a length of the photomultiplier, and wherein the light interaction region and the collection region are positioned on opposite sides of the avalanche region.

Still another aspect of the present disclosure provides a photomultiplier with a field-shaping multi-well avalanche detector, comprising: a lower insulator; an a-Se photoconductive layer; and an upper insulator, wherein the a-Se photoconductive layer is between the lower insulator and the upper insulator, wherein a light interaction region, an avalanche region, and a collection region are provided along a length of the photomultiplier, wherein the light

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interaction region and the collection region are positioned on opposite sides of the avalanche region, wherein the light interaction region comprises an upper optical window and a lower optical window, wherein the upper optical window is configured for input of first light from above the field-shaping multi-well avalanche detector, and wherein the lower optical window is configured for input of second light from below the field-shaping multi-well avalanche detector.

Another aspect of the present disclosure provides a photomultiplier with a field-shaping multi-well avalanche detector, comprising: a lower insulator; an upper insulator; an a-Se photoconductive layer between the lower insulator and the upper insulator; a high voltage source positioned at a distal end of the light interaction region; and a collector positioned at a distal end of the collection region, wherein a light interaction region, an avalanche region, and a collection region are provided along a length of the photomultiplier, wherein the light interaction region and the collection region are positioned on opposite sides of the avalanche region, and wherein the high voltage source and the collector are positioned on opposite horizontal ends of the field-shaping multi-well avalanche detector to form an electric field therebetween.

Still another aspect of the present disclosure provides a photomultiplier with a field-shaping multi-well avalanche detector, comprising: a lower insulator; an a-Se photoconductive layer; an upper insulator; and a plurality of grids positioned at predetermined intervals along a horizontal length of the avalanche region, wherein the a-Se photoconductive layer is between the lower insulator and the upper insulator, wherein a light interaction region, an avalanche region, and a collection region are provided along a length of the photomultiplier, wherein the light interaction region and the collection region are positioned on opposite sides of the avalanche region, and wherein the plurality of grids form a plurality of lateral Frisch grids with a plurality of amplification stages therebetween.

Another aspect of the present disclosure provides a photomultiplier with a field-shaping multi-well avalanche detector, comprising: a lower insulator; an upper insulator; an a-Se photoconductive layer between the lower insulator and the upper insulator; and a plurality of

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grids positioned along a horizontal length of an avalanche region, wherein a light interaction region, the avalanche region, and a collection region are provided along a length of the photomultiplier, wherein the light interaction region and the collection region are positioned on opposite sides of the avalanche region, and wherein the plurality of grids are biased to create a high-field region and provide multi-stage avalanche gain.

Still another aspect of the present disclosure provides a photomultiplier with a field-shaping multi-well avalanche detector, comprising: a lower insulator; an a-Se photoconductive layer; and an upper insulator, wherein the a-Se photoconductive layer is between the lower insulator and the upper insulator, wherein a light interaction region, an avalanche region, and a collection region are provided along a length of the photomultiplier, wherein the light interaction region and the collection region are positioned on opposite sides of the avalanche region, wherein the light interaction region comprises an upper optical window and a lower optical window, wherein the upper optical window is configured for input of first light from above the detector, and wherein the lower optical window is configured for input of second light from below the detector.

Another aspect of the present disclosure provides a photomultiplier with a field-shaping multi-well avalanche detector, comprising: a lower insulator; an upper insulator; an a-Se photoconductive layer between the lower insulator and the upper insulator; a high voltage source positioned at a distal end of the light interaction region; and a collector positioned at a distal end of the collection region, wherein a light interaction region, an avalanche region, and a collection region are provided along a length of the photomultiplier, wherein the light interaction region and the collection region are positioned on opposite sides of the avalanche region, and wherein the high voltage source and the collector are positioned on opposite horizontal ends of the detector to form an electric field therebetween.

Still another aspect of the present disclosure provides a photomultiplier with a field-shaping multi-well avalanche detector, comprising: a lower insulator; an a-Se photoconductive layer; an upper insulator; and a plurality of grids positioned at predetermined intervals along a horizontal length of the avalanche region, wherein the a-Se photoconductive layer is between

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the lower insulator and the upper insulator, wherein a light interaction region, an avalanche region, and a collection region are provided along a length of the photomultiplier, wherein the light interaction region and the collection region are positioned on opposite sides of the avalanche region, and wherein the plurality of grids form a plurality of lateral Frisch grids with a plurality of amplification stages therebetween.

Still yet another aspect of the present disclosure provides a photomultiplier with a field-shaping multi-well avalanche detector, comprising: a lower insulator; an upper insulator; an a-Se photoconductive layer between the lower insulator and the upper insulator; and a plurality of grids positioned along a horizontal length of an avalanche region, wherein a light interaction region, the avalanche region, and a collection region are provided along a length of the photomultiplier, wherein the light interaction region and the collection region are positioned on opposite sides of the avalanche region, and wherein the plurality of grids are biased to create a high-field region and provide multistage avalanche gain.

BRIEF DESCRIPTION OF THE DRAWINGS

The above and other aspects, features and advantages of certain embodiments of the present invention will be more apparent from the following detailed description taken in conjunction with the accompanying drawings, in which:

FIG. 1 is a profile view of a multi-well selenium photomultiplier (Se-PM) according to an embodiment of the present disclosure;

FIG. 2 illustrates field intensity in the Se-PM of FIG. 1;

FIG. 3 is a profile view of a multi-well Se-PM according to another embodiment of the present disclosure;

FIG. 4 illustrates field intensity in the Se-PM of FIG. 3;

FIG. 5 is a graph showing weighting potential versus distance of the present disclosure;

FIG. 6(a) is a graph of field voltage versus distance of the present disclosure; and

FIG. 6(b) is a graph of gain versus distance of the present disclosure.

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DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

The following detailed description of certain embodiments of the present invention will be made with reference to the accompanying drawings. In describing the invention, explanation about related functions or constructions known in the art are omitted for the sake of clearness in understanding the concept of the invention, to avoid obscuring the invention with unnecessary detail.

Disclosed herein is a solid-state avalanche radiation detector, and a method for constructing same, using amorphous material as the photoconductive layer. The solid-state avalanche radiation detector is based on field-shaping by localizing the high-field avalanche region between a plurality of low-field regions, improving on the devices of Sauli [7], U.S. Pat. No. 6,437,339 to Lee, et al., U.S. Pat. No. 8,129,688 to A. H. Goldan, et al., U.S. Pat. Publ. No. 2016/0087113 A1 of U.S. Appl. No. 14,888,879 to A. H. Goldan, et al. and U.S. Pat. Publ. No. 2015/0171232 A1 of U.S. Appl. No. 14/414,607 to A. H. Goldan, et al.

FIG. 1 is a profile view of a multi-well Se-PM according to an embodiment of the present disclosure. FIG. 2 illustrates field intensity in the Se-PM of FIG. 1 during operation thereof.

As shown in FIGs. 1 and 2, a photomultiplier device is provided with a cascaded lateral, i.e., horizontal, SWAD structure 100, a lower insulator 112, an a-Se photoconductive layer 130, and an upper insulator 114. The a-Se photoconductive layer 130 is positioned between the lower insulator 112 and the upper insulator 114. Dielectric is interchangeable with insulator. A light interaction region 140, an avalanche region 150, and a collection region 180 are provided along a length of the cascaded lateral SWAD structure 100. The light interaction region 140 and the collection region 180 are adjacent to and positioned on opposite sides of the avalanche region 150.

The avalanche region 150 is formed in a longitudinal direction, i.e., along a horizontal orientation, via photolithography, rather than by a vertical film thickness, as in conventional devices. Defining the avalanche region 150 via photolithography creates a stable, reliable and repeatable detector architecture.

The light interaction region 140 has an upper, i.e., front, optical window 141 and a lower, i.e., back, optical window 142, for input of first light 144 and second light 146, from above and below the cascaded lateral SWAD structure 100, respectively.

A high voltage source 149 is provided at a distal end of the light interaction region 140, and a collector 182 is provided at a distal end of the collection region 180, with the high voltage source 149 and the collector 182 provided on opposite horizontal ends of the cascaded lateral SWAD structure 100.

The a-Se photoconductive layer 130 is positioned between the lower insulator 112 and the upper insulator 114. The lower insulator 112 is preferably Polyimide and the upper insulator 114 is preferably a chemical vapor deposited poly(p-xylylene) polymer that provides a moisture and dielectric barrier, e.g., Parylene. The lower insulator 112 is positioned adjacent to and above a substrate 110, which is preferably a glass substrate.

A plurality of grids 152, 154, 156, 158, i.e., lateral Frisch grids, are provided at predetermined intervals along a horizontal length of the avalanche region 150 of the cascaded lateral SWAD structure 100, with each grid of the plurality of grids 152, 154, 156, 158 provided at one or more predetermined distances from an adjacent another grid of the plurality of grids 152, 154, 156, 158.

In the multi-well Se-PM of FIG. 1, each grid of the plurality of grids has opposite first and second parts. That is, grid 152 includes a first part 152a and a second part 152b formed on the upper insulator 114 and lower insulator 112, respectively. Grid 154 includes first part 154a and a second part 154b, grid 156 includes first part 156a and a second part 156b, and grid 158 includes first part 156a and a second part 156b, which are similarly positioned. The grid electrodes can be formed in or on respective the insulator. Since the electric field is low, the grid electrodes need not be encapsulated in the insulator.

A high-field region is created by biasing the electrodes of each grid of the plurality of grids 152, 154, 156, 158, thereby achieving multi-stage avalanche gain. Accordingly, a practical Se-PM is provided with insulating blocking layers that eliminate the formation of field hot-spots inside the a-Se, and also eliminates charge injection from metal to semiconductor, with all grid electrodes being encapsulated with dielectric/insulator.

FIG. 2 shows four amplification stages 172, 174, 176, 178 formed between each of the plurality of grids. FIG. 2 shows voltage variation, with an absence of field hot-spots within the a-Se. Increasing a ratio of the upper and lower optical windows 141, 142 to the overall size of the avalanche region 150 reduces a fill factor due to the amplification stages, at the expense of lower time-resolution.

Reducing the number of grids reduces gain. Alternatively, increasing the number of grids provides corresponding gain increases. Essentially unlimited gain can be obtained by increasing the number of grids. Since grids are added in a horizontal orientation by photolithography, the gain is provided without increasing vertical thickness.

FIG. 3 is a profile view of a multi-well Se-PM according to another embodiment of the present disclosure. FIG. 4 illustrates field intensity in the Se-PM of FIG. 3 during operation thereof.

As shown in FIGs. 3 and 4, a cascaded lateral SWAD structure 300 is provided with a plurality of grids 352, 354, 356, 358 positioned in interaction region 340, with a plurality of high voltage dividers 349a, 349b, 349c, 349d in the light interaction region 340. The plurality of grids 352, 354, 356, 358 are positioned only on a lower insulator 312. A collection region 380 is provided with collector 382. The other components of FIG. 3 correspond in operation to FIG. 1, and description thereof is not repeated here for conciseness.

FIG. 4 shows Gaussian electric field shaping of the lateral SWAD by localizing the high-field avalanche region in gain stage 372 between grid 352 and grid 354; and in gain stage 374 between grid 354 and grid 356; in gain stage 376 between grid 356 and grid 358; thereby confining avalanche multiplication between the grid planes and eliminating charge injection from the metal electrodes. Such horizontal multi-stage field shaping achieves gain levels that are not possible with a single-stage vertical avalanche device.

FIGs. 3 and 4 show a weighting potential distribution for the Se-PM, with the grids of the lateral SWAD providing an extremely strong near-field effect in an immediate vicinity of the collector. Signal is induced and sensed by the readout electronics only when avalanched holes drift pass the final grid electrode and reach the collector, as shown in FIG. 4. Accordingly, nearly ideal UTD charge sensing is provided with only a physical limit on detector's time resolution in a spatial width of the charge cloud.

As shown in FIG. 4, hot spots are formed on a side of grid 352 closest to gain stage 372, on a side of grid 354 closes to gain stage 374, on both sides of grid 356, and on one side of grid 358 closest to gain stage 378.

FIG. 5 is a graph showing weighting potential versus distance of the present disclosure. FIG. 5 illustrates the weighting potential distribution of hole-only charge collection during operation of the horizontal photomultiplier of the present disclosure.

FIG. 6(a) is a graph of field voltage versus distance of the present disclosure of cascaded Gaussian field-shaping regions using lateral SWADs with four gain stages. FIG. 6(b) is a graph of gain versus distance of the present disclosure, showing simulated avalanche gain g_{av} of $\sim 10^6$ [V/V] for a Se-PM with n = 4.

While the invention has been shown and described with reference to certain aspects thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the spirit and scope of the present invention as defined by the appended claims and equivalents thereof.

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What is claimed is:

1. A photomultiplier with a field-shaping multi-well avalanche detector, comprising:

an insulator;

a-Se photoconductive layer adjacent to the insulator;

a light interaction region;

an avalanche region;

a collection region;

a plurality of high voltage dividers positioned in the light interaction region; and

a collector positioned at a distal end of the collection region,

wherein the light interaction region, the avalanche region, and the collection region are provided along a length of the photomultiplier, and

wherein the light interaction region and the collection region are positioned on opposite sides of the avalanche region.

2. The photomultiplier of claim 1, wherein the avalanche region is formed in a horizontal orientation, and the a-Se photoconductive layer is formed on lower insulator in a vertical orientation.

3. The photomultiplier of claim 1 or 2, wherein the avalanche region is formed via photolithography.

4. The photomultiplier of any one of claims 1 to 3, wherein the light interaction region comprises an optical window configured for input of light to be detected.

5. The photomultiplier of any one of claims 1 to 4, further comprising a plurality of grids along a horizontal length of the avalanche region.

6. The photomultiplier of claim 5, wherein each grid of the plurality of grids is provided at a predetermined distance from an adjacent another grid of the plurality of grids.

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7. The photomultiplier of claim 5 or 6, wherein the plurality of grids form a plurality of lateral grids with a plurality of amplification stages therebetween, and wherein multi-stage avalanche gain is confined between the plurality of grids and charge injection from metal electrodes is eliminated.

8. The photomultiplier of claim 5 or 6, wherein the plurality of grids are biased to create a high-field region, to provide multi-stage avalanche gain that eliminates formation of field hot-spots inside the a-Se, and eliminates charge injection from high-field metal-semiconductor interfaces.

9. A photomultiplier with a field-shaping multi-well avalanche detector, comprising:

a lower insulator;

an a-Se photoconductive layer; and

an upper insulator,

wherein the a-Se photoconductive layer is between the lower insulator and the upper insulator,

wherein a light interaction region, an avalanche region, and a collection region are provided along a length of the photomultiplier,

wherein the light interaction region and the collection region are positioned on opposite sides of the avalanche region,

wherein the light interaction region comprises an upper optical window and a lower optical window,

wherein the upper optical window is configured for input of first light from above the field-shaping multi-well avalanche detector, and

wherein the lower optical window is configured for input of second light from below the field-shaping multi-well avalanche detector.

10. The photomultiplier of claim 9, wherein the a-Se photoconductive layer is positioned between the lower insulator and the upper insulator.

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11. The photomultiplier of claim 9 or 10, wherein the avalanche region is formed in a horizontal orientation.

12. The photomultiplier of any one of claims 9 to 11, wherein the avalanche region is formed via photolithography.

13. The photomultiplier of any one of claims 9 to 12, further comprising:
a high voltage source positioned at a distal end of the light interaction region; and
a collector positioned at a distal end of the collection region.

14. The photomultiplier of claim 13, wherein the high voltage source and the collector are positioned on opposite horizontal ends of the field-shaping multi-well avalanche detector to form an electric field therebetween.

15. The photomultiplier of any one of claims 9 to 14, further comprising a plurality of grids along a horizontal length of the avalanche region.

16. The photomultiplier of claim 15, wherein each grid of the plurality of grids provided at a predetermined distance from an adjacent another grid of the plurality of grids.

17. The photomultiplier of claim 15 or 16, wherein the plurality of grids form a plurality of lateral Frisch grids with a plurality of amplification stages therebetween.

18. The photomultiplier of any one of claims 15 to 17, wherein the plurality of grids are biased to create a high-field region, to provide multi-stage avalanche gain that eliminates formation of field hot-spots inside the a-Se.

19. The photomultiplier of claim 18, wherein the multi-stage avalanche gain is confined between grid planes of the plurality of grids and charge injection from metal electrodes is eliminated.

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20. The photomultiplier of any one of claims 15 to 19, wherein the plurality of grids are positioned at predetermined intervals along the horizontal length of the avalanche region.

21. The photomultiplier of any one of claims 9 to 20, wherein the a-Se photoconductive layer and the upper insulator are formed on the lower insulator in a vertical orientation.

22. A photomultiplier with a field-shaping multi-well avalanche detector, comprising:

a lower insulator;

an upper insulator;

an a-Se photoconductive layer between the lower insulator and the upper insulator;

a high voltage source positioned at a distal end of the light interaction region; and

a collector positioned at a distal end of the collection region,

wherein a light interaction region, an avalanche region, and a collection region are provided along a length of the photomultiplier,

wherein the light interaction region and the collection region are positioned on opposite sides of the avalanche region, and

wherein the high voltage source and the collector are positioned on opposite horizontal ends of the field-shaping multi-well avalanche detector to form an electric field therebetween.

23. A photomultiplier with a field-shaping multi-well avalanche detector, comprising:

a lower insulator;

an a-Se photoconductive layer;

an upper insulator; and

a plurality of grids positioned at predetermined intervals along a horizontal length of the avalanche region,

wherein the a-Se photoconductive layer is between the lower insulator and the upper insulator,

wherein a light interaction region, an avalanche region, and a collection region are provided along a length of the photomultiplier,

wherein the light interaction region and the collection region are positioned on opposite sides of the avalanche region, and

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wherein the plurality of grids form a plurality of lateral Frisch grids with a plurality of amplification stages therebetween.

24. A photomultiplier with a field-shaping multi-well avalanche detector, comprising:

a lower insulator;

an upper insulator;

an a-Se photoconductive layer between the lower insulator and the upper insulator; and

a plurality of grids positioned along a horizontal length of an avalanche region,

wherein a light interaction region, the avalanche region, and a collection region are provided along a length of the photomultiplier,

wherein the light interaction region and the collection region are positioned on opposite sides of the avalanche region, and

wherein the plurality of grids are biased to create a high-field region and provide multi-stage avalanche gain.

25. The photomultiplier of claim 24, wherein the multi-stage avalanche gain eliminates field hot-spot formation inside the a-Se.

26. The photomultiplier of claim 24 or 25, wherein the plurality of grids are biased to eliminate charge injection from high-field metal-semiconductor interfaces.

27. The photomultiplier of any one of claims 24 to 26, wherein the multi-stage avalanche gain is confined between grid planes of the plurality of grids.

28. The photomultiplier of claim 27, wherein confining the multi-stage avalanche gain between grid planes of the plurality of grids eliminates charge injection from metal electrodes.

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29. A photomultiplier with a field-shaping multi-well avalanche detector, comprising:

a lower insulator;

an a-Se photoconductive layer; and

an upper insulator,

wherein the a-Se photoconductive layer is between the lower insulator and the upper insulator,

wherein a light interaction region, an avalanche region, and a collection region are provided along a length of the photomultiplier,

wherein the light interaction region and the collection region are positioned on opposite sides of the avalanche region,

wherein the light interaction region comprises an upper optical window and a lower optical window,

wherein the upper optical window is configured for input of first light from above the detector, and

wherein the lower optical window is configured for input of second light from below the detector.

30. The photomultiplier of claim 29, wherein the a-Se photoconductive layer is positioned between the lower insulator and the upper insulator.

31. The photomultiplier of claim 29 or 30, wherein the avalanche region is formed in a horizontal orientation.

32. The photomultiplier of any one of claims 29 to 31, wherein the avalanche region is formed via photolithography.

33. The photomultiplier of any one of claims 29 to 32, further comprising:

a high voltage source positioned at a distal end of the light interaction region; and

a collector positioned at a distal end of the collection region.

34. The photomultiplier of claim 33, wherein the high voltage source and the collector are positioned on opposite horizontal ends of the detector to form an electric field therebetween.

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35. The photomultiplier of any one of claims 29 to 34, further comprising a plurality of grids along a horizontal length of the avalanche region.

36. The photomultiplier of claim 35, wherein the plurality of grids are positioned at predetermined intervals along the horizontal length of the avalanche region.

37. The photomultiplier of claim 35 or 36, wherein each grid of the plurality of grids provided at a predetermined distance from an adjacent another grid of the plurality of grids.

38. The photomultiplier of any one of claims 35 to 37, wherein the plurality of grids form a plurality of lateral Frisch grids with a plurality of amplification stages therebetween.

39. The photomultiplier of any one of claims 35 to 38, wherein the plurality of grids are biased to create a high-field region, to provide multi-stage avalanche gain that eliminates formation of field hot-spots inside the a-Se.

40. The photomultiplier of claim 39, wherein the multi-stage avalanche gain is confined between grid planes of the plurality of grids and charge injection from metal electrodes is eliminated.

41. The photomultiplier of any one of claims 29 to 40, wherein the a-Se photoconductive layer and the upper insulator are formed on the lower insulator in a vertical orientation.

42. A photomultiplier with a field-shaping multi-well avalanche detector, comprising:

a lower insulator;

an upper insulator;

an a-Se photoconductive layer between the lower insulator and the upper insulator;

a high voltage source positioned at a distal end of the light interaction region; and a collector positioned at a distal end of the collection region,

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wherein a light interaction region, an avalanche region, and a collection region are provided along a length of the photomultiplier,

wherein the light interaction region and the collection region are positioned on opposite sides of the avalanche region, and

wherein the high voltage source and the collector are positioned on opposite horizontal ends of the detector to form an electric field therebetween.

43. A photomultiplier with a field-shaping multi-well avalanche detector, comprising:

a lower insulator;

an a-Se photoconductive layer;

an upper insulator; and

a plurality of grids positioned at predetermined intervals along a horizontal length of the avalanche region,

wherein the a-Se photoconductive layer is between the lower insulator and the upper insulator,

wherein a light interaction region, an avalanche region, and a collection region are provided along a length of the photomultiplier,

wherein the light interaction region and the collection region are positioned on opposite sides of the avalanche region, and

wherein the plurality of grids form a plurality of lateral Frisch grids with a plurality of amplification stages therebetween.

44. A photomultiplier with a field-shaping multi-well avalanche detector, comprising:

a lower insulator;

an upper insulator;

an a-Se photoconductive layer between the lower insulator and the upper insulator; and

a plurality of grids positioned along a horizontal length of an avalanche region,

wherein a light interaction region, the avalanche region, and a collection region are provided along a length of the photomultiplier,

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wherein the light interaction region and the collection region are positioned on opposite sides of the avalanche region, and

wherein the plurality of grids are biased to create a high-field region and provide multistage avalanche gain.

45. The photomultiplier of claim 44, wherein the multi-stage avalanche gain eliminates field hot-spot formation inside the a-Se.

46. The photomultiplier of claim 44 or 45, wherein the plurality of grids are biased to eliminate charge injection from high-field metal-semiconductor interfaces.

47. The photomultiplier of any one of claims 44 to 46, wherein the multi-stage avalanche gain is confined between grid planes of the plurality of grids.

48. The photomultiplier of claim 47, wherein confining the multi-stage avalanche gain between grid planes of the plurality of grids eliminates charge injection from metal electrodes.

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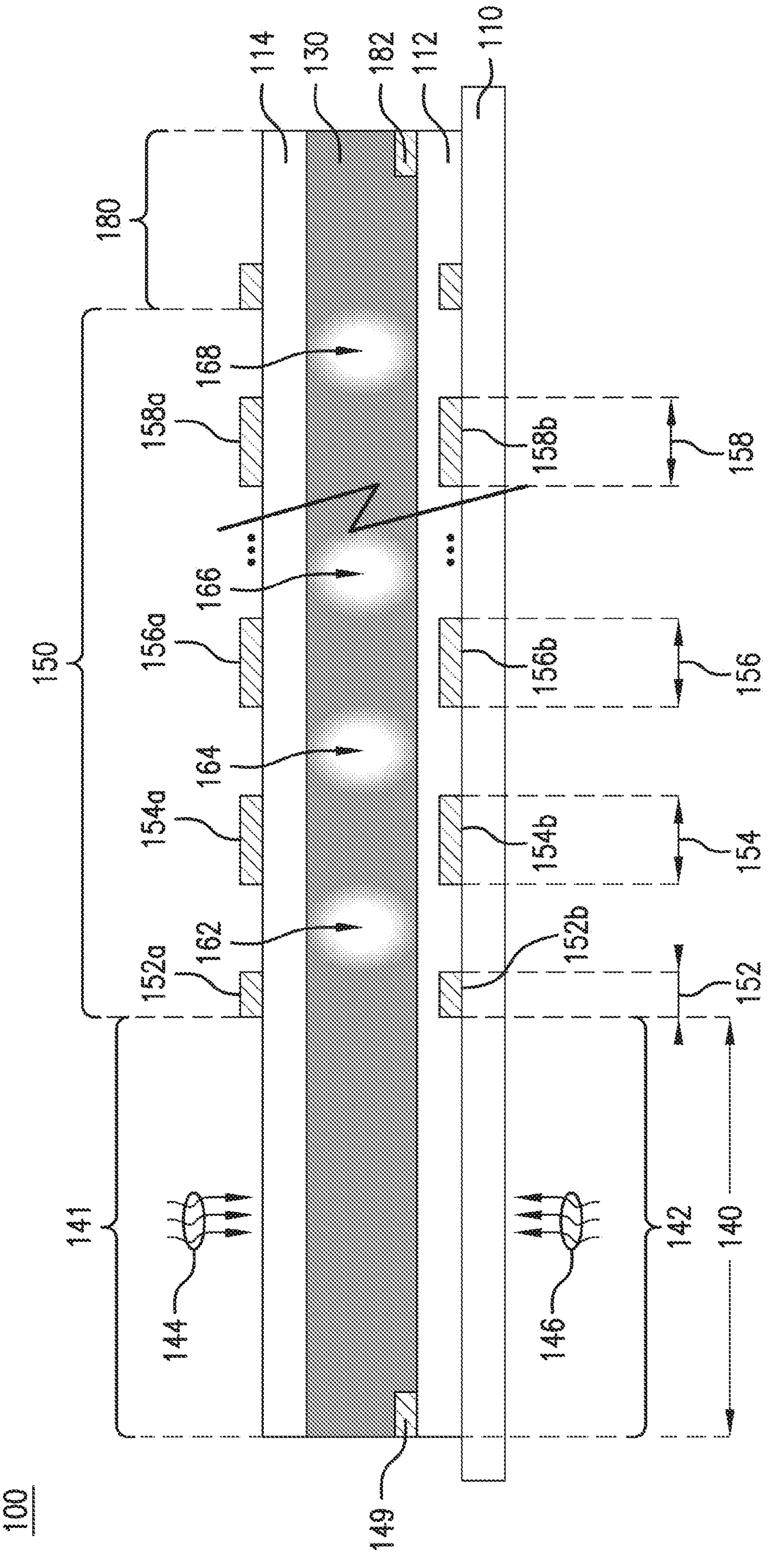

100
110
112
114
130
182
180
150
141
142
140
144
146
149
152
152a
152b
154
154a
154b
156
156a
156b
158
158a
158b
162
164
166
168

FIG. 1

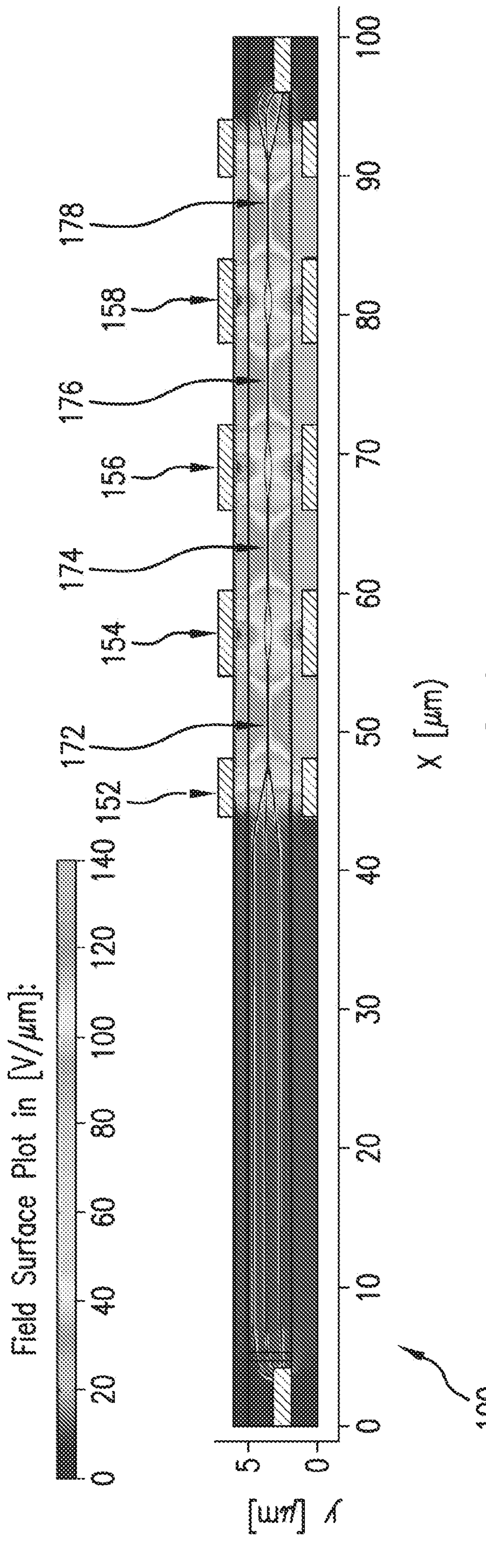

Field Surface Plot in [V/μm]:
0
20
40
60
80
100
120
140
152
172
154
174
156
176
158
178
y [μm]
5
0
0
10
20
30
40
50
60
70
80
90
100
x [μm]
100

FIG. 2

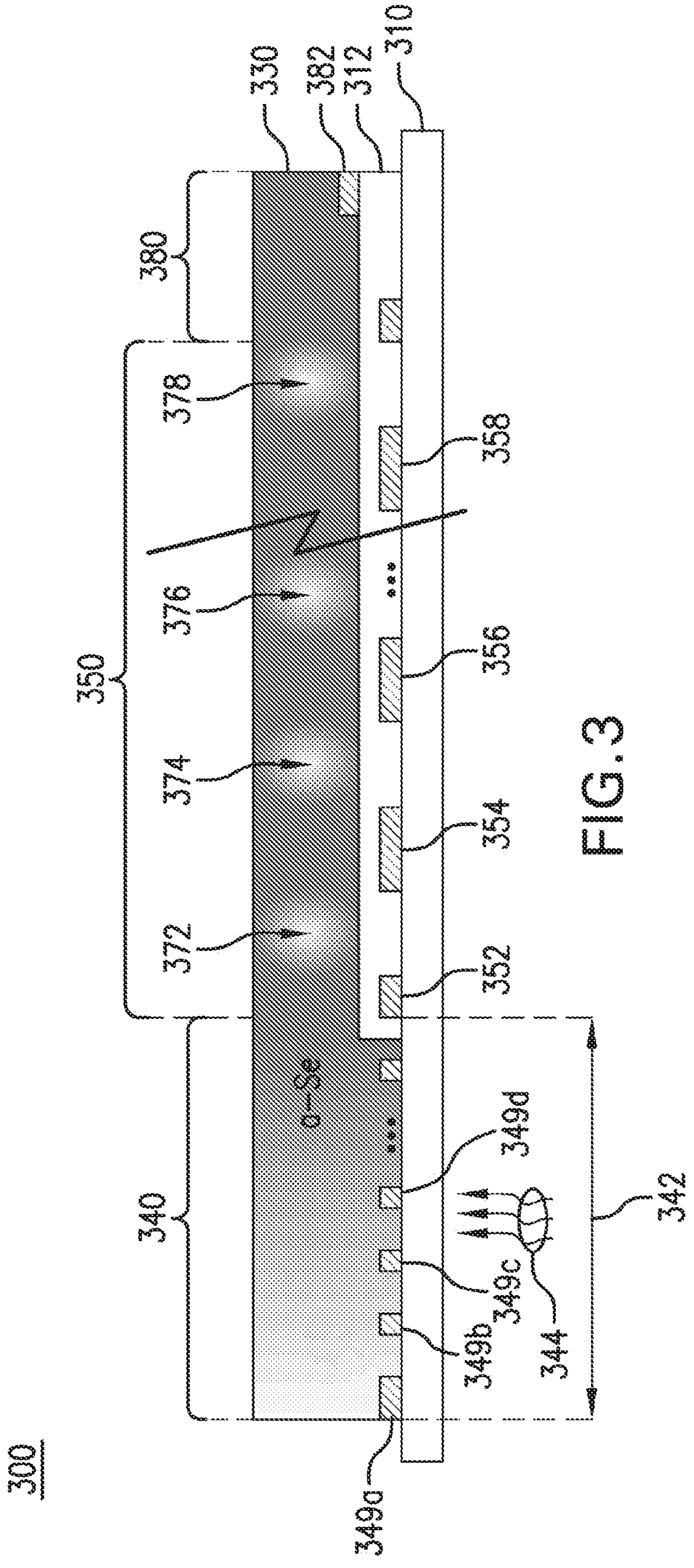

300
310
312
382
330
380
350
340
342
344
349a
349b
349c
349d
352
354
356
358
372
374
376
378
a-Se

FIG. 3

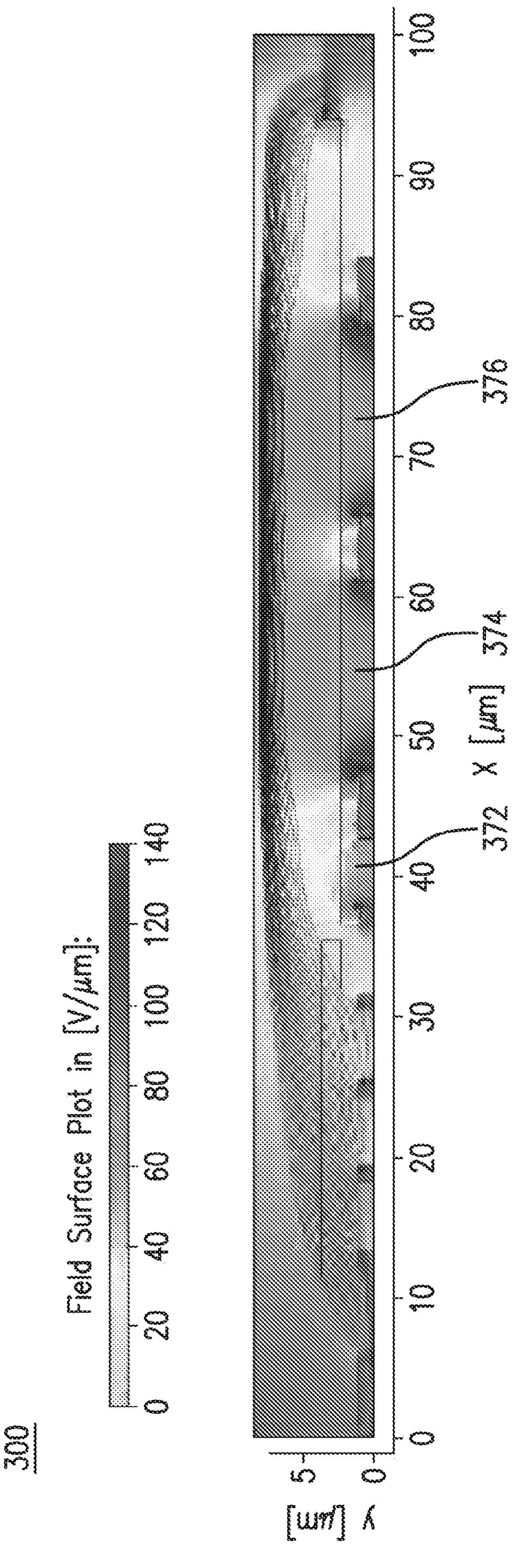

300
Field Surface Plot in [V/μm]:
0
20
40
60
80
100
120
140
y [μm]
5
0
X [μm]
0
10
20
30
40
50
60
70
80
90
100
372
374
376

FIG. 4

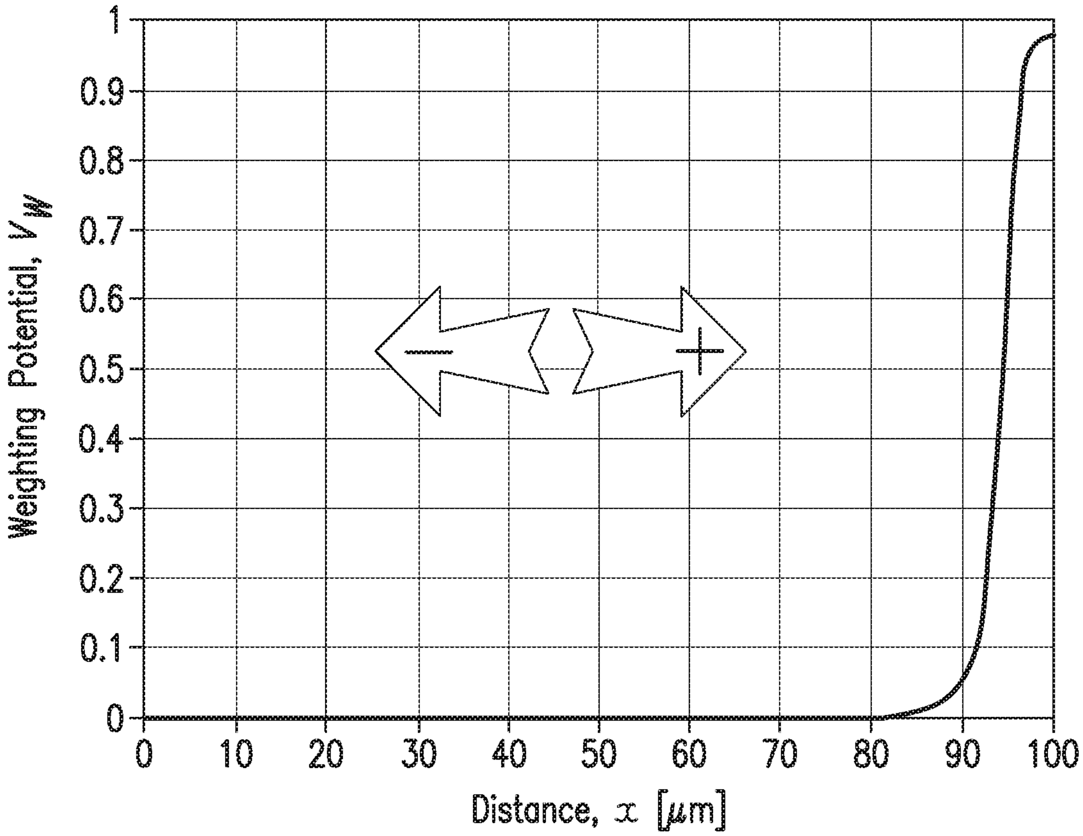

1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Weighting Potential, V_W
0
10
20
30
40
50
60
70
80
90
100
Distance, x [μm]
−
+

FIG.5

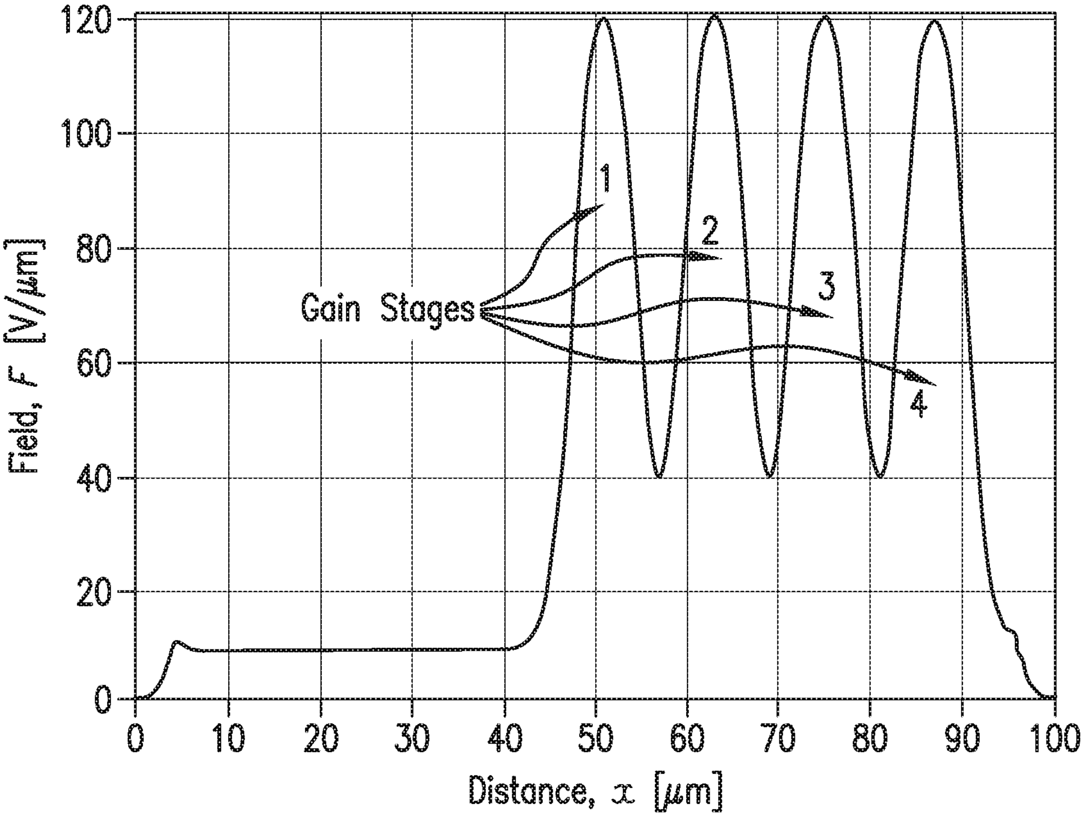

120
100
80
60
40
20
0
Field, F [V/μm]
Gain Stages
1
2
3
4
0 10 20 30 40 50 60 70 80 90 100
Distance, x [μm]

FIG.6A

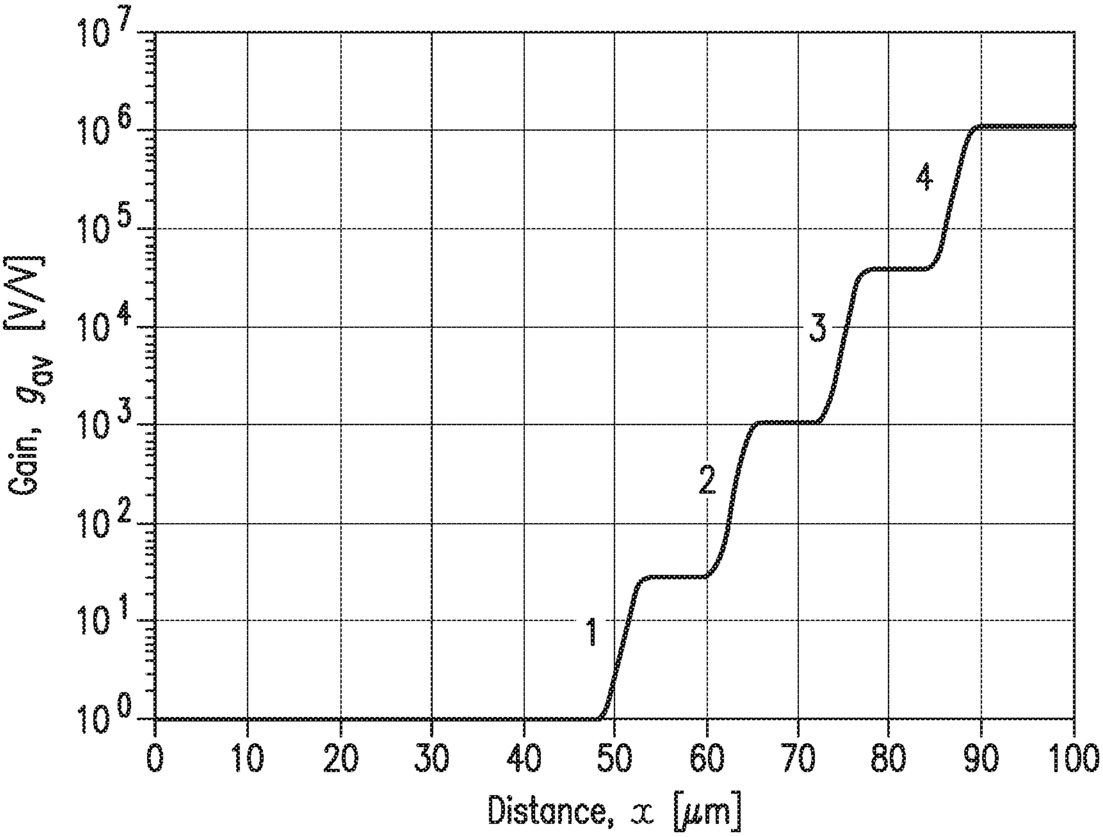
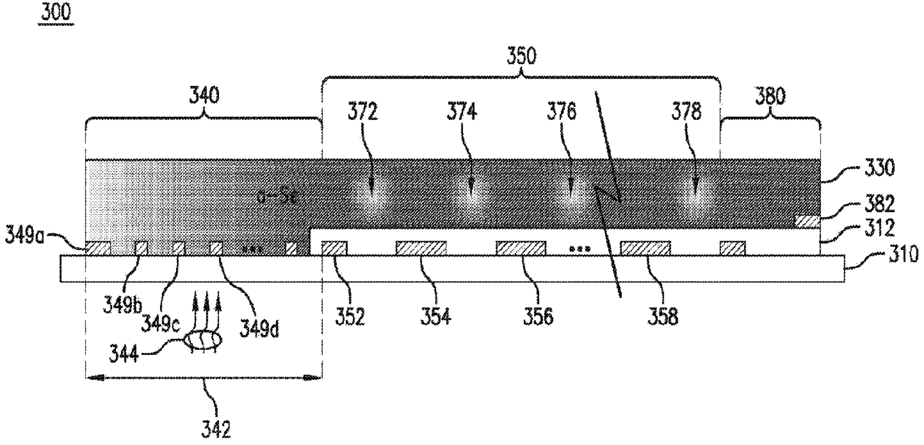

10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
Gain, g_av [V/V]
1
2
3
4
0 10 20 30 40 50 60 70 80 90 100
Distance, x [μm]

FIG.6B



300
350
340
380
372
374
376
378
330
a-Se
382
349a
312
310
349b
349c
349d
352
354
356
358
344
342