

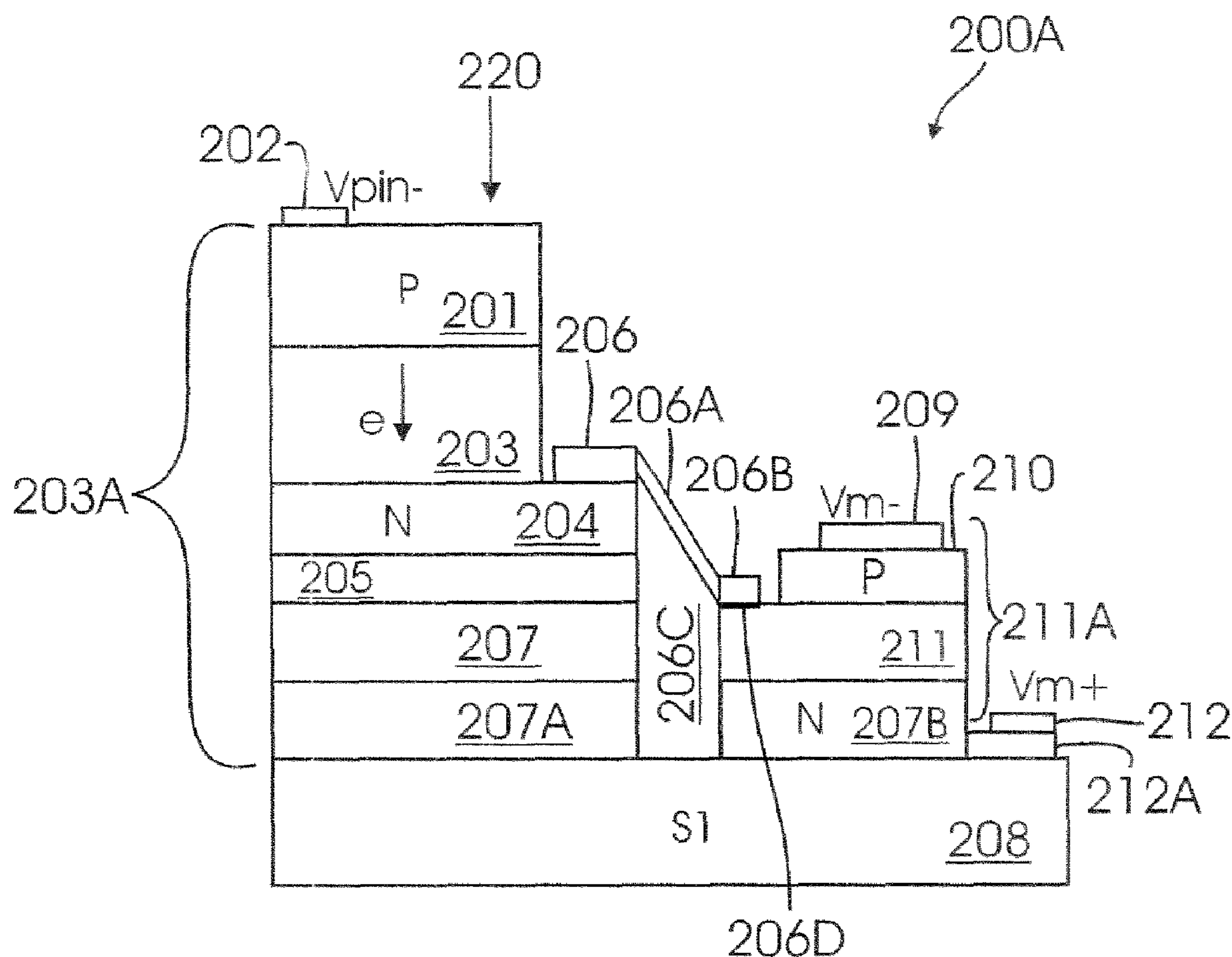
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## Publication Classification

(57) **ABSTRACT**

An avalanche photodiode detector is provided. The avalanche photodiode detector comprises an absorber region having an absorption layer for receiving incident photons and generating charged carriers; and a multiplier region having a multiplication layer; wherein the multiplier region is on a mesa structure separate from the absorber region and is coupled to the absorber region by a bridge for transferring charged carriers between the absorber region and multiplier region.

(22) Filed: **Nov. 27, 2006**



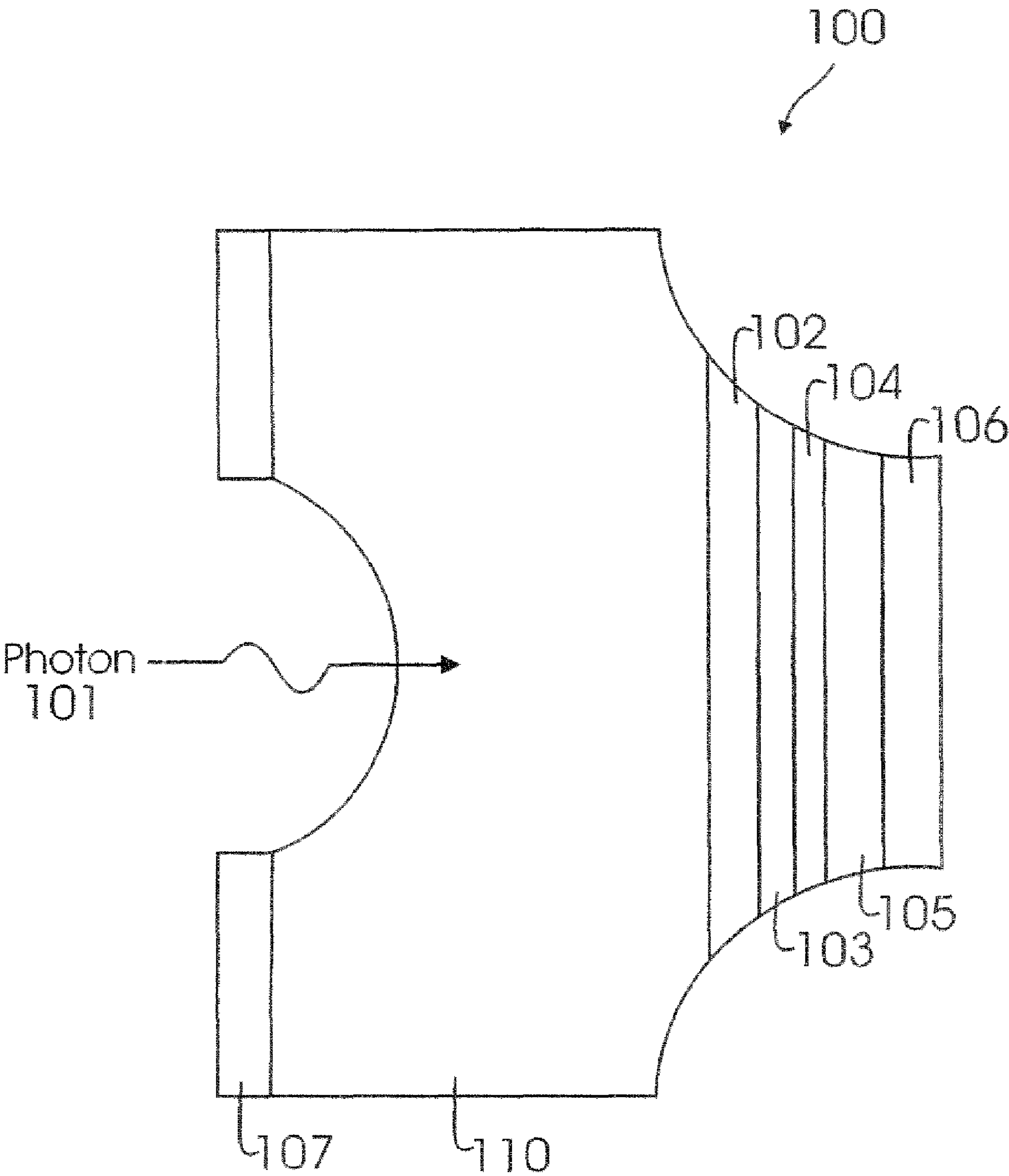


FIG. 1

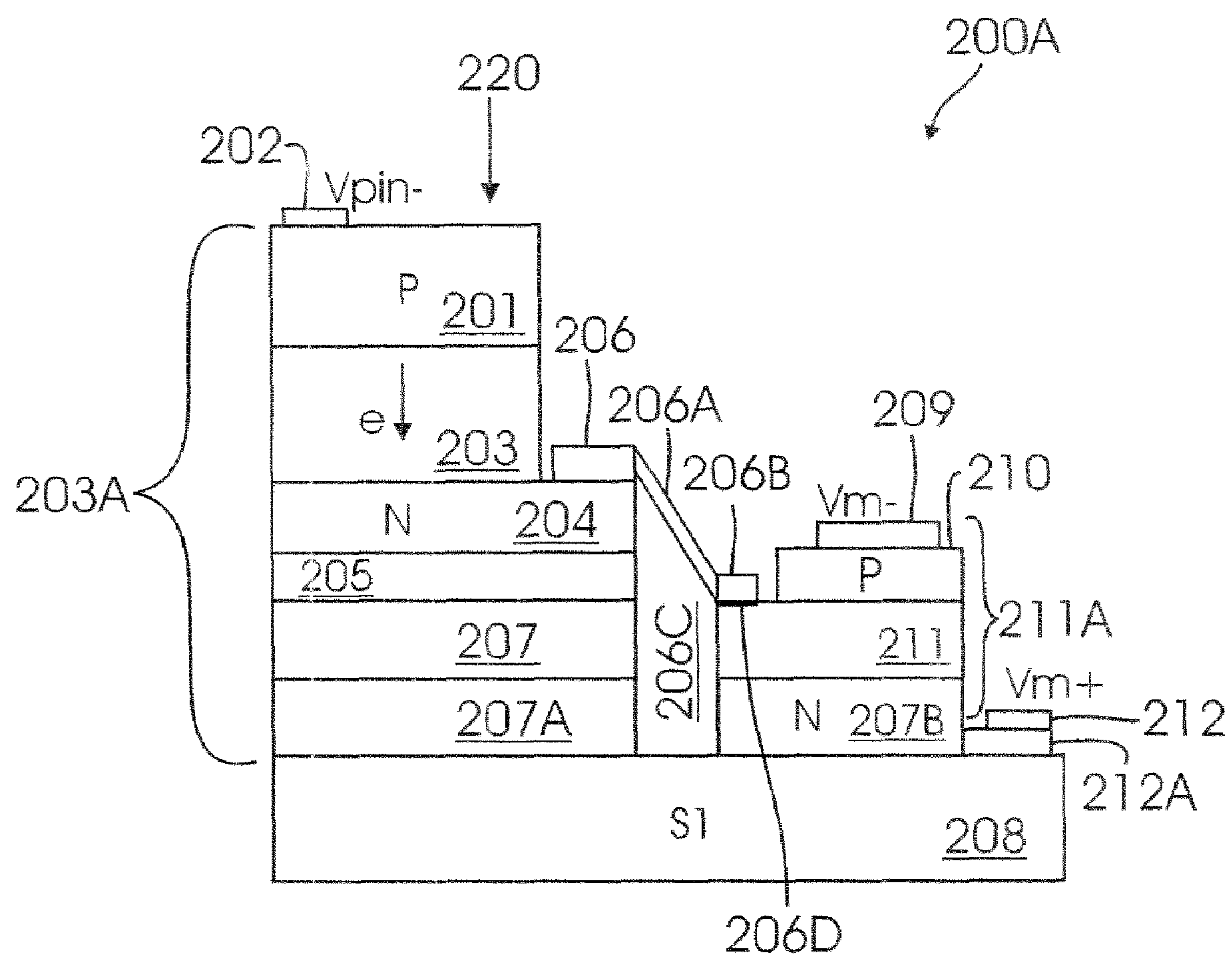


FIG. 2A

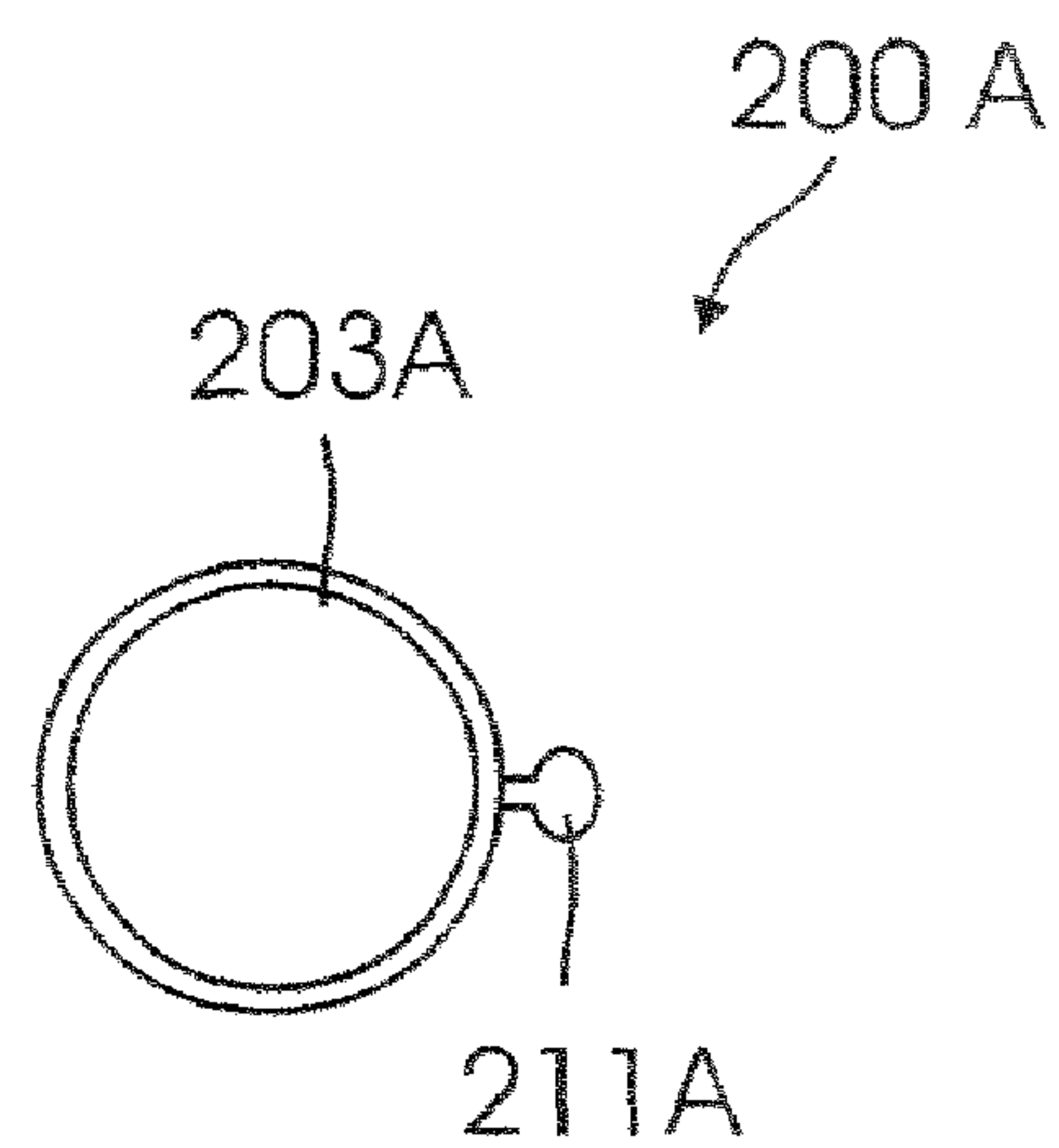


FIG. 2B



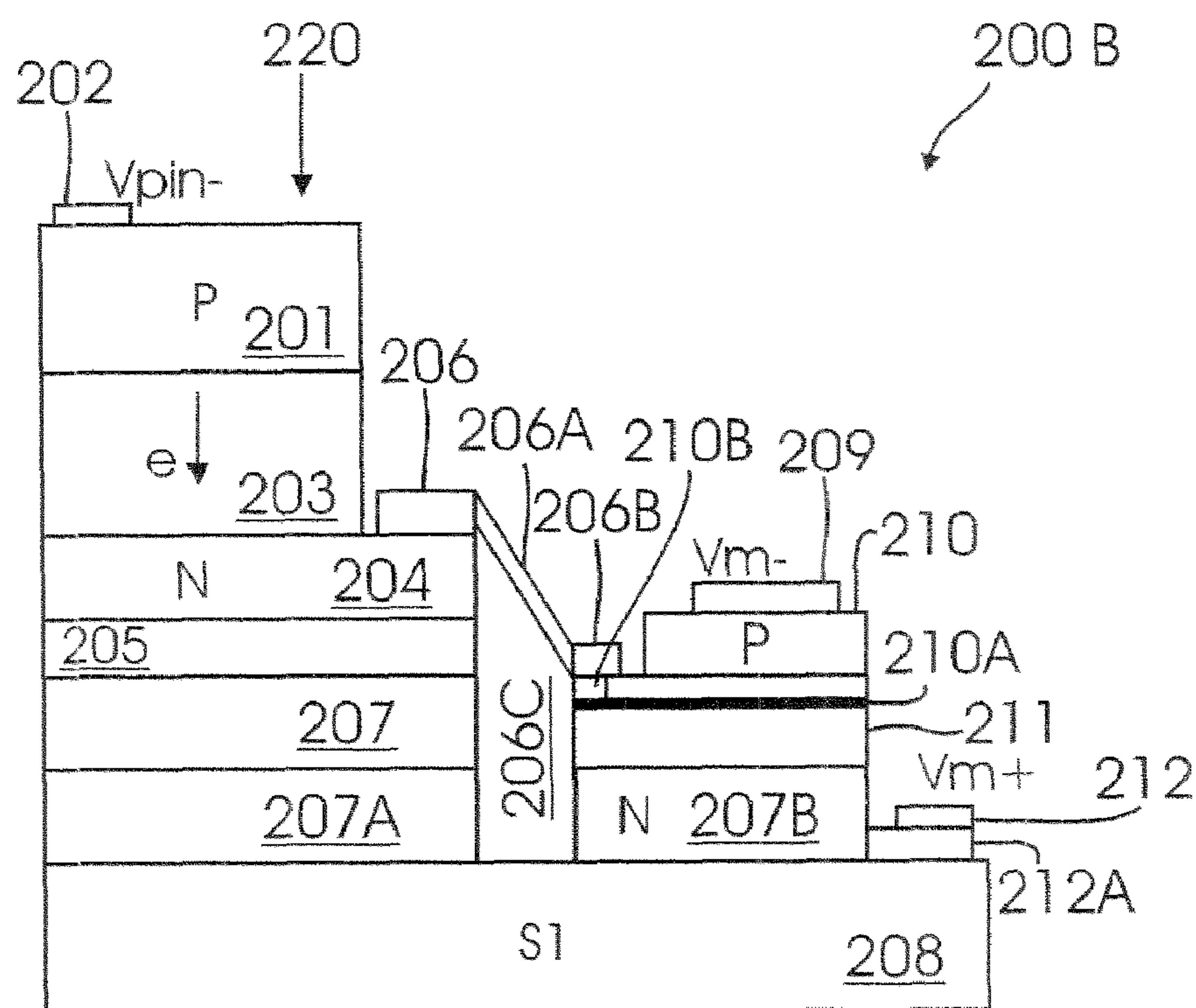


FIG. 2C

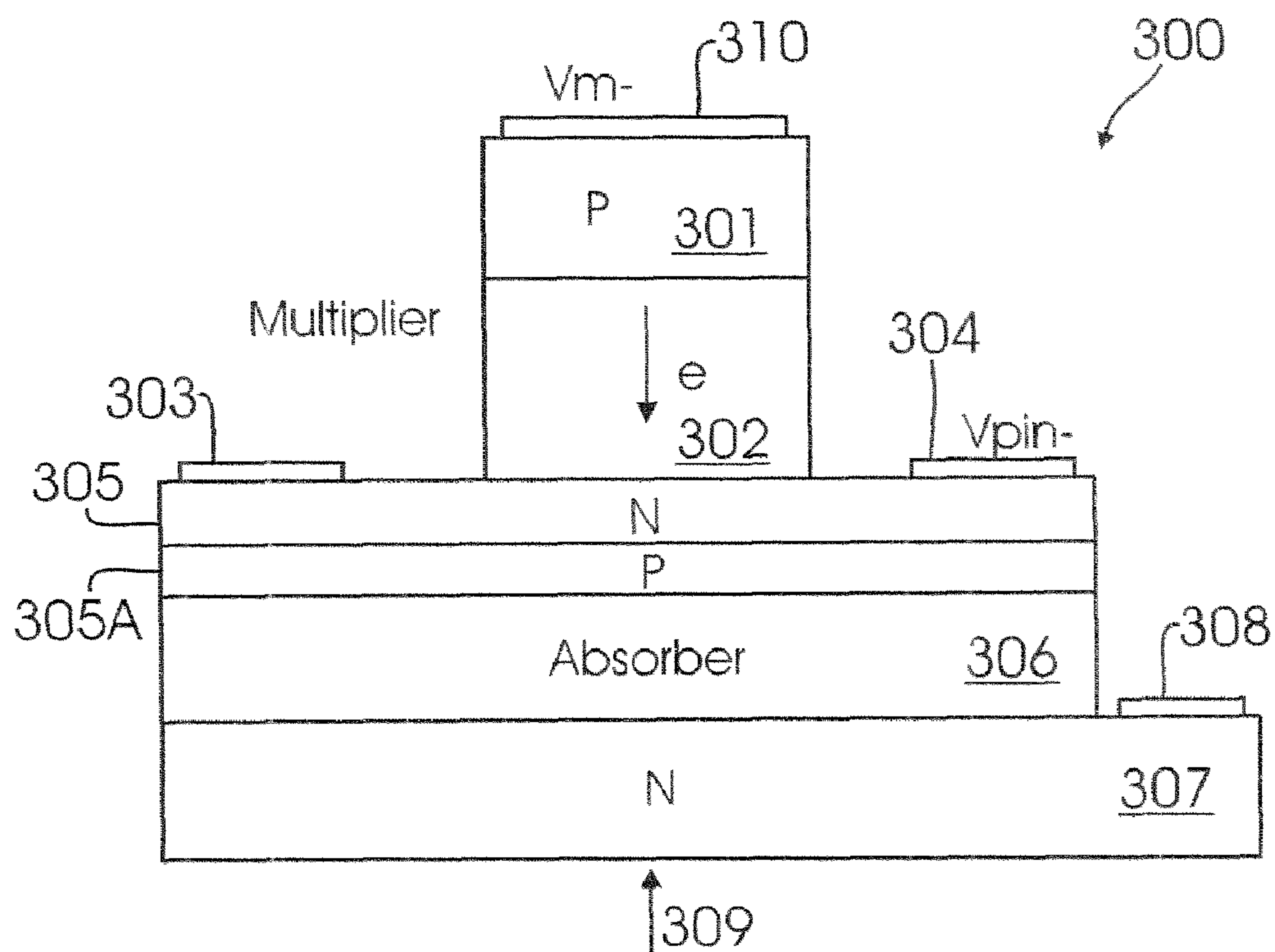


FIG. 3

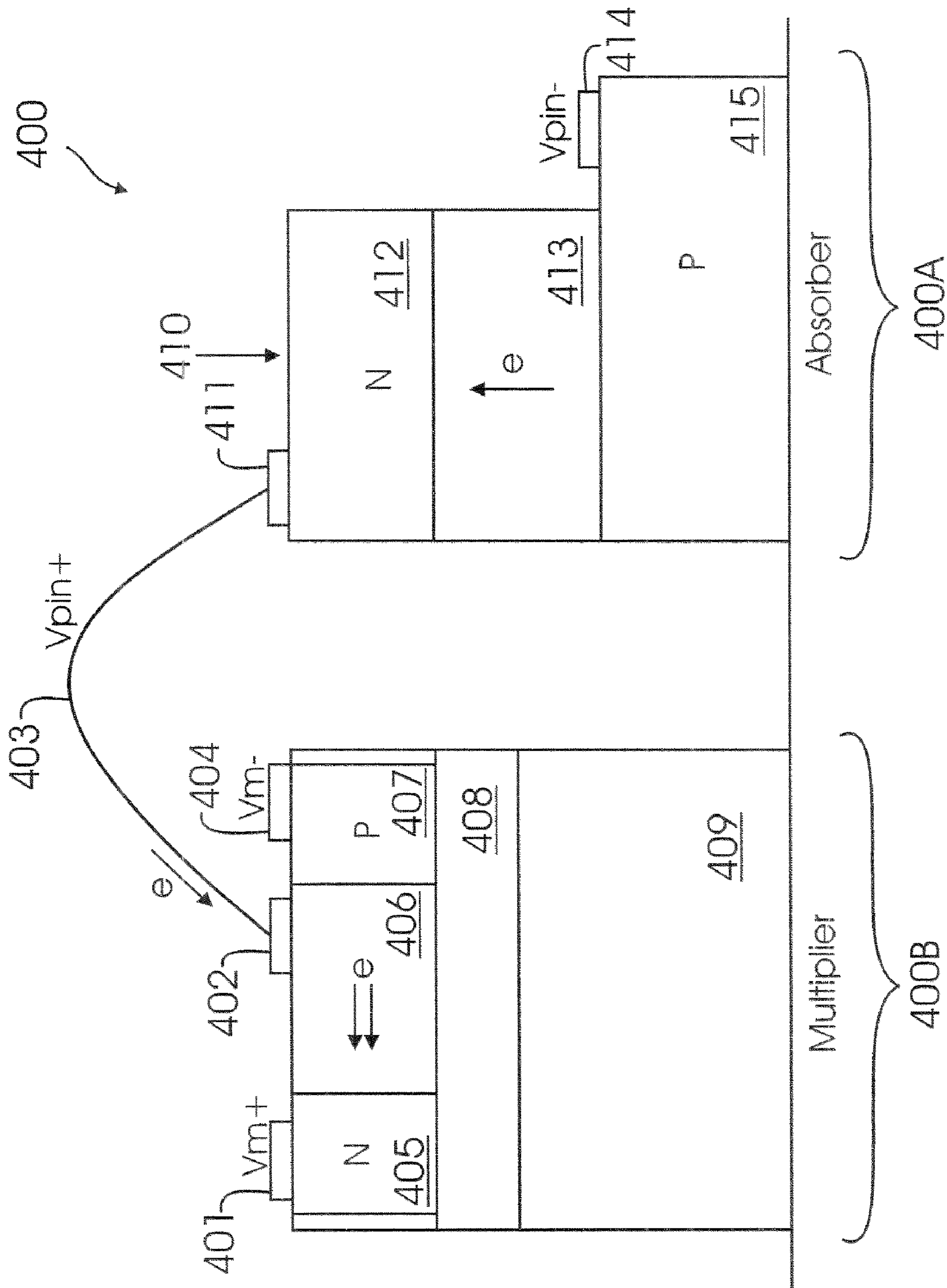


FIG. 4



## AVALANCHE PHOTODIODE DETECTOR

### 1. FIELD OF THE INVENTION

**[0001]** The present invention relates generally to photodiode detectors, and more particularly to avalanche photodiode detectors.

### 2. BACKGROUND

**[0002]** Avalanche photodiode detectors (APDs) are photo-sensitive devices that detect optical power by converting an input signal (photons) to an electrical signal. The input signal is amplified by an “avalanche effect” when carriers are infected in an area with high electrical field. This occurs because multiple electron-hole pairs are created for each absorbed photon.

**[0003]** An APD typically comprises of a plurality of stacked layers including a multiplication layer and an absorption layer on a semiconductor substrate. The absorption layer absorbs incident photons to create electron/holes that are transferred to the multiplication layer. The multiplication layer multiplies the electrons/holes. This occurs when electron/holes have sufficient energy to create a new electron and hole. Initial carriers and newly created carriers may create additional electrons and holes (hence the name “avalanche”) by repeating the multiplication process.

**[0004]** In a conventional APD, all layers are grown in one epitaxial growth. This may lead to some interface defects. Due to interface defects there may be some carrier traps and recombination centers, which reduce overall quantum efficiency and after pulsing performance of an APD.

**[0005]** Furthermore, simultaneous growth of absorption and multiplication layers does not provide flexibility in selecting different materials for these layers.

**[0006]** Therefore there is a need for an avalanche photodiode that overcomes the foregoing problems in conventional APDs.

### SUMMARY OF THE INVENTION

**[0007]** In one aspect of the present invention, an avalanche photodiode detector is provided. The avalanche photodiode detector comprises an absorber region having an absorption layer for receiving incident photons and generating charged carriers; and a multiplier region having a multiplication layer; wherein the multiplier region is on a mesa structure separate from the absorber region and is coupled to the absorber region by a bridge for transferring charged carriers from the absorber region to the multiplier region.

**[0008]** In another aspect of the present invention, an avalanche photodiode detector is provided. The avalanche photodiode detector comprises an absorption layer formed over a semiconductor substrate, for receiving incident photons and generating charged carriers; a contact layer formed on the absorption layer; a first P-doped layer formed on the absorption layer; a multiplication layer formed over the contact layer; a second P doped layer formed on the multiplication layer; a first contact provided on the second P-doped layer; a second contact provided on the contact layer; and a third contact provided on the substrate; wherein the voltage difference across the first contact and the second contact controls the multiplication layer, and the voltage difference between the second contact and the third contact controls the absorption layer.

**[0009]** In yet another aspect of the present invention, an avalanche photodiode detector is provided. The avalanche photodiode detector comprises an absorber region having an absorption layer for receiving incident photons and generating charged carriers; a multiplier region having a multiplication layer; wherein the multiplier region is built on a separate mesa structure, and may be of a different material than the absorber region; and is wired to the absorber region to transfer charged carriers.

**[0010]** This brief summary has been provided so that the nature of the invention may be understood quickly. A more complete understanding of the invention may be obtained by reference to the following detailed description of the preferred embodiments thereof in connection with the attached drawings.

### BRIEF DESCRIPTION OF THE DRAWINGS

**[0011]** The foregoing features and other features of the present invention will now be described with reference to the drawings of a preferred embodiment. In the drawings, the same components have the same reference numerals. The illustrated embodiment is intended to illustrate, but not to limit the invention. The drawings include the following Figures:

**[0012]** FIG. 1 shows a block diagram of an APD structure;

**[0013]** FIG. 2A shows a schematic of an APD structure on separate mesas, according to an aspect of the present invention;

**[0014]** FIG. 2B shows the top view of the APD structure of FIG. 2A;

**[0015]** FIG. 2C shows a schematic of a APD structure with a N-Contact and quantum wells, according to an aspect of the present invention;

**[0016]** FIG. 3 shows an APD structure with single mesa, according to an aspect of the present invention; and

**[0017]** FIG. 4 shows a schematic of a hybrid APD structure, according to an aspect of the present invention.

### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

**[0018]** In one aspect of the present invention, a three terminal APD structure with separate absorption and multiplication layer (also referred to as “TT-SAM APD or APD”) is provided. The absorption layer and multiplication layer may be grown separately and hence are controlled independently. This allows one to select different materials for the absorption and multiplication layer. The APD of the present invention also provides an additional terminal. The additional terminal enables individual control of bias across an absorption (“Absorber”) region and a multiplication (“Multiplier”) region.

**[0019]** To facilitate an understanding of APD structure, a general overview of a conventional APD structure will be described. The specific structural components and layers of APD of the present invention, will then be described with reference to general structure of APD.

**[0020]** FIG. 1 shows a top level block diagram of a conventional APD structure. APD 100 includes a P-InP substrate layer 110; a P-InP buffer layer 102 and an N-InP multiplication layer 103; an n-InGaAsP grading (or bandgap-transition) layer and charge layer 104 of an intermediate bandgap; and an n-InGaAs narrow-bandgap absorption layer 105. Charge layer 104 is generally provided to control the electric fields in the absorption and multiplication layers, 103 and 105, respec-



tively, and reduce charge accumulation at the interface between them. Layers **106** and **107** are metal contacts, which may be made of, for example, AuInZn or AuSn.

[0021] During operation of APD **100**, incident photons **101** are absorbed in absorption layer **105**, and charged carriers (holes and electrons) are created through a photogeneration process. Charged carriers are multiplied in multiplication layer **103** resulting in internal gain within APD **100**. Incident photons **101** may enter APD through substrate layer **110** (as shown in FIG. **1**) or through absorption layer **105**.

[0022] In APD **100**, electric field profile is controlled by charge layer **104**. To ensure a low electric field in absorption layer **105** and a high field in multiplication layer **103**, doping level in charge layer **104** needs to be precisely controlled. In practice, it is difficult to control doping level in charge layer **105**. The present invention provides an APD structure that eliminates use of charge layer, overcoming inherent problems associates with the use of charge layer.

[0023] FIGS. **2A** and **2B** show an APD structure according to one aspect of the present invention. FIG. **2A** is a cross-sectional view and FIG. **2B** is a top view of APD structure **200**.

[0024] Referring to FIG. **2A**, a three terminal SAN APD structure **200A** (also referred to as “TT-SAM” or “APD” interchangeably) is shown. APD **200A** comprises of separate absorber region **203A** and multiplier region **211A** formed over a semiconductor substrate layer **208**. Substrate layer **208** is preferably a semi-insulating layer. In one aspect, substrate layer **208** may be an indium phosphide (InP) layer. Absorber region **203A** and multiplier region **211A** may be grown in one epitaxial run or separately.

[0025] Absorber region **203A** includes a first insulating layer **207A**. Insulating layer **207A** is formed of InAlAs and may have a thickness between 0.7  $\mu\text{m}$ -1.5  $\mu\text{m}$ . Above first insulating layer **207A**, a second insulating layer **207** is formed. Second insulating layer **207** is formed of InAlAs and has a thickness of between 0.2  $\mu\text{m}$ -1.5  $\mu\text{m}$ . Above second insulating layer **207**, a third insulating layer **205** is provided. This third insulating layer **205** may be formed of InP and has a thickness of about 0.2  $\mu\text{m}$  to 0.5  $\mu\text{m}$ .

[0026] Above third insulator layer **205**, an N-doped contact layer **204** is formed. N-doped contact layer **204** is formed of a suitable material having appropriate thickness. In one aspect, N-doped contact layer **204** is formed of InP, and may have a thickness between 0.5  $\mu\text{m}$ -1.0  $\mu\text{m}$ .

[0027] First insulating layer **207A**, second insulating layer **207** and third insulating layers **205** act as insulators and do not allow flow of charge/electrons to the substrate layer **208**. This also prevents any unintentional leakage of current through N-doped contact layer **204** to the substrate layer **208**.

[0028] Above contact layer **204**, an absorption layer **203** is provided. Absorption layer **203** may be formed of a material having bandgap of 0.5-0.7 eV. In one aspect, absorption layer **203** is formed of InGaAs, and may have a thickness between 1-5  $\mu\text{m}$ .

[0029] Above absorption layer **203**, a wide bandgap window layer **201** may be provided. In one aspect, window layer **201** may be formed of InP or InGaAsP. Contacts **202** and **206** are also provided on absorber region **203A**. A separate bias is applied across absorber region **203A** and potential difference between contacts **202** and **206** controls absorber region **203A** functionality.

[0030] Multiplier region **211A** includes an N-doped layer **207B**. N-doped Layer **207B** is preferably formed of InAlAs and has a thickness of between of 0.7  $\mu\text{m}$  to 1.5  $\mu\text{m}$ .

[0031] A multiplication layer **211** is grown on N-doped layer **207B**. In one aspect, multiplication layer **211** comprises InAlAs. Multiplication layer **211** may have a thickness range of 0.02  $\mu\text{m}$  to 1.5  $\mu\text{m}$ .

[0032] It is within the scope of the present invention to use other suitable materials known in the art to form absorption layer **203**, contact layer **204**, window layer **201**, multiplication layer **211**, N-doped **207B**, P-doped layer **210** or substrate layer **208**.

[0033] Above multiplication layer **211**, a P-doped InP layer **210** is grown. P-doped layer **210** may have a thickness in the range of 0.2  $\mu\text{m}$  to 0.5  $\mu\text{m}$ .

[0034] Contacts **209** and **212** are also provided in multiplier region **211A**. Contact **212** is provided over a conducting layer **212A**. Conducting layer **212A** is formed over the substrate layer **208**. Conducting layer **212A** has a thickness of 0.35  $\mu\text{m}$  to 0.75  $\mu\text{m}$ .

[0035] A separate bias is applied across multiplier region **211A** and voltage difference between contacts **209** and **212** controls the electric field in multiplication layer **211**.

[0036] Absorber region **203A** and multiplier region **211A** are joined by a metal contact bridge **206A** via contacts **206** and **206B**. Metal bridge **206A** transfers charge between absorber region **203A** and multiplier region **211A**. A passivation layer **206C** (an insulator region) may also be provided beneath the metal bridge **206A**.

[0037] The bias condition of Schottky junction **206D**, which is influenced by voltage difference between contacts **202** and **209**, controls carrier injection from absorber region **203A** to multiplier region **211A**. **206** and **200B** are metal contacts and may be N-metal contacts, while contacts **202** and **209** may be P-metal contacts. Metal bridge **206A** and metal contacts **206** and **206B** may be a formed of a connected metal having the same potential.

[0038] Incident photons **220** enter APD structure **200A** via layer **201**. Incident photons **220** are absorbed in absorber region **203A**, and charged carriers (holes and electrons) are created through a photogeneration process. The charged carriers are injected into multiplier **211A** and initiate an avalanche multiplication resulting in internal gain within APD **200A**.

[0039] Absorber region **203A** and multiplier region **211A** are decoupled and both regions have individual isolated mesas. Therefore the size and type of material for absorber region **203A** and multiplier region **211A** can be controlled independently.

[0040] For APD **200A**, dark current, dark count rate (DCR), device capacitance and bandwidth benefit from a smaller multiplier region **211A** area. A larger absorber region **203A** area with low electric field collects photons efficiently without significant sacrifice in all these aspects.

[0041] To maintain efficient carrier injection from absorber region **203A** into multiplier region **211A**, a Schottky junction **206D** is used in contact with undoped multiplication layer **211**. Schottky junction **206D** is used to inject photon-generated electrons into multiplier region **211A**. This junction is adjacent to but not in the primary carrier path in the avalanche process and hence avoids recombination by holes generated by avalanching in the multiplier region **211A**. The avalanche-generated holes are collected at contact **209**.



[0042] APD 200A does not have a charge layer. Instead of charge layer, the carrier injection from absorber region 203A to multiplier region 211A is controlled by the bias condition of Schottky junction 206D, which is influenced by the 2-D potential distribution at the injection contact. In operation, this distribution is determined by the voltage differences between contacts 202 and 209, and 209 and 212.

[0043] In an alternative embodiment shown in FIG. 2C, injection efficiency of an APD 200B may further be improved with an N-well (210B) and quantum wells (210A). By replacing Schottky junction 206D with a p-n junction, leakage current from injection is minimized 2-D electron gas formed in quantum well (210A) transports injected electrons to a high field region quickly and effectively while keeping holes from deviating from the multiplier region 211A. In the photon counting applications, because there is no hole to recombine in the beginning of a gate pulse, the injected elections will trigger the avalanche events effectively, or realize higher quantum efficiency. In one aspect of the present invention, quantum well 110A may have a thickness range from 50 Å-100 Å, and the N-well may be formed by diffusion or ion-implantation.

[0044] It is within the scope of present invention to simultaneously grow a part of absorber region and multiplier region. This simultaneously grown region may then be separated and processed independently. As shown in APD 200A and 200C, first insulating layer 207A and N-doped layer 207B are formed of InAlAs. After growing a layer of InAlAs, it is separated into at least two parts. One part, 207A, forms an insulating layer while the other part is doped to form N-doped layer 207B. Similarly, multiplication layer 211 and P-doped layer are grown simultaneously as second insulating layer 207 and third insulating layer 205.

[0045] FIG. 3 shows APD 300 in another aspect of the present invention. APD 300 includes a single mesa structure. Substrate layer 307 is formed of a semiconductor material, for example InP. Substrate layer 307 may have a thickness range of 200 μm-500 μm. An absorption layer 306 of thickness 1 μm-5 μm is grown on substrate layer 307. Absorption layer 306 is preferably an InGaAs layer. Above absorption layer 306, a P-doped layer 305A is formed. P-doped layer 305A may have a thickness of 1 μm to 5 μm.

[0046] A N-doped layer 305 of InP is formed over P-doped layer 305A. N-doped layer 305 may have a thickness of about 0.1 μm. A multiplication layer 302 of InP or InAlAs is formed on doped layer 305. Multiplication layer 302 may have a thickness between 0.02 μm-1.0 μm. A P-layer 301 of InP is formed above multiplication layer 302 having a thickness between 0.2 μm-1.0 μm.

[0047] It is within the scope of the invention to use other suitable materials known in the art to form absorption layer 306, P-doped layer 305A, N-doped layer 305, multiplication layer 302 or P-layer 302.

[0048] Contact 310 is provided over P-layer 301 while N-doped layer 305 has two contacts 303 and 304. Photons 309 enter via substrate layer 307. Incident photons 309 are absorbed in absorption layer 306, and charged carriers (holes and electrons) are created through a photogeneration process. The charged carriers initiate an avalanche multiplication in multiplication layer 302 resulting in internal gain within APD 300.

[0049] In APD 300, charge is injected when electrons pass through N-doped layer 305. In order to maintain efficient carrier injection and reverse bias in the absorption layer 306

while sustaining electric field uniformity in multiplication layer 302, a tunnel Junction with a p-type layer between 305 and 306 is inserted between the two function regions.

[0050] APD 300 also does not have a charge layer. Instead of charge layer, bias difference between contacts 310 and 303 controls multiplication layer 302. Similarly, voltage difference between contacts 304 and 308 controls absorption layer 306.

[0051] APD configuration 300 has a larger absorption layer 306 area coupled to a smaller multiplication mesa 302. The smaller multiplication mesa 302 reduces dark count rate while minimizing bias across absorption layer 306, thus increasing overall usable quantum efficiency of APD 300.

[0052] In yet another aspect of the present invention, a hybrid APD 400 as shown in FIG. 4, is provided. By hybrid it means that different materials having different characteristic properties may be used for forming absorber region 400A and multiplier region 400B of APD 400. Conventionally, it has been difficult to integrate Silicon material with InGaAs or InP or similar materials to form APDs. In one aspect of the present invention, hybrid APD 400, overcomes these material constraints.

[0053] In APD 400, different materials for multiplier region 400B and absorber region 400A are used, and wafer bonding may be used to join the different materials.

[0054] Absorber region 400A is preferably formed of InP while multiplier region 400B may be formed of Silicon. It is well known that material growth constraints exist between materials like InGaAs or InP and silicon. However, with hybrid integration, these material growth constraints between absorber and multiplier regions (400A and 400B) are avoided providing a wider spectrum of materials available for device optimization.

[0055] Absorber region 400A includes a P-doped layer 415 of InP or InAlAs of thickness range of 0.2 μm-1.0 μm. Absorption layer 413 of InGaAs is formed over P-doped layer 415. Absorption layer 413 may have a thickness range of 0.2 μm-0.5 μm.

[0056] An N-doped layer 412 of InP, InAlAs or InGaAsP is formed over absorption layer 413. N-doped layer 412 may have a thickness range of 0.2 μm-0.5 μm. Contacts 411 and 414 control the bias across absorption layer.

[0057] Multiplier region 400B includes a silicon substrate layer 409. An insulator layer 408 of silicon oxide is formed over silicon substrate layer 409. Above insulator layer 408, there is N-well region (405) and P-well region (407). A multiplication layer 406 is provided between N-well region (405) and P-well region (406) for transferring high field from N-well to P-well.

[0058] Absorber region 400A is wire bound (403) to a multiplier region 400B via metal contacts 402 and 411. Schottky junction 402 is employed to improve injection efficiency for photon-generated carriers. In order to avoid recombination with avalanche-generated holes, Schottky junction 402 avoids mainstream avalanche current, while a small potential difference between  $V_{pin+}$  (404) and  $V_{m-}$  (401) helps to inject electrons.

[0059] Voltage difference between contacts 401 and 404 determines bias for multiplier region 400B while voltage difference between contacts 411 and 414 determines bias for absorber region 400A.

[0060] Incident photons 410 enter absorber region 400A through N-doped layer 412. Incident photons 410 are absorbed in the absorber region 400A, and charged carriers



(holes and electrons) are created through a photogeneration process. The charged carriers are injected through the Schottky junction (402) and initiate an avalanche multiplication in multiplier region 400B resulting in internal gain within APD 400.

[0061] APD 400 eliminates charge layer and interface defects associated with the use of charge layer. APD 400 also allows one to select different types of materials for multiplier region 400B and absorber region 400A.

[0062] The foregoing APDs (200A, 200B, 300 and 400) of the present invention provide better quantum efficiency. APDs of the present invention eliminate use of charge layer between absorption layer and multiplication layer by introducing an extra terminal between absorber region (203A or 400A) and multiplier region (211A or 400B). The electric fields in absorber (203A or 400A) and multiplier regions (211A or 400B) are controlled individually by the potential differences between the three terminals. The decoupling of the two functional regions, multiplier region and absorber region, helps in maintaining a low but sufficient field in the absorber. This also allows one to independently optimize the size, material and layer structure of the two regions.

[0063] While the adaptive aspects of the present invention list specific materials with specific thickness for forming absorption layer, multiplication layer, contact layer, P-doped layer and N-doped layer, it will be understood by those skilled in the art that similar materials, exhibiting similar properties of varying thickness may be used, and equivalents may be substituted for elements thereof without departing from the true scope of the adaptive aspects of the present invention.

[0064] Although the present invention has been described with reference to specific embodiments, these embodiments are illustrative only and not limiting. Many other applications and embodiments of the present invention will be apparent in light of this disclosure and the following claims.

1. An avalanche photodiode detector, comprising:  
an absorber region formed over a semiconductor substrate and having an absorption layer for receiving incident photons and generating charged carriers, at least one insulating layer electrically isolating the absorber region from the semiconductor substrate; and  
a multiplier region formed over the semiconductor substrate and having a multiplication layer;  
wherein the multiplier region is on a mesa structure separate from the absorber region and is coupled to the absorber region by a bridge, for transferring charged carriers from the absorber region to the multiplier region.
2. The avalanche photodiode detector of claim 1, wherein the absorber region further includes a pair of first contacts.
3. The avalanche photodiode detector of claim 2, wherein bias across the absorber region is maintained by the first contacts.
4. The avalanche photodiode detector of claim 1, wherein the multiplier region further includes a pair of second contacts.
5. The avalanche photodiode detector of claim 4 wherein bias across the multiplier region is maintained by the second contacts.
6. The avalanche photodiode detector of claim 1, wherein the absorber region and the multiplier region are formed over a semiconductor substrate layer.

7. The avalanche photodiode detector of claim 1, wherein a Schottky junction is used for injecting carriers in the multiplication layer.

8. The avalanche photodiode detector of claim 1, wherein a quantum well and an N-well is used for injecting carriers in the multiplication layer.

9. The avalanche photodiode detector of claim 1, wherein the bridge is a metal bridge.

10. The avalanche photodiode detector of claim 1 absorber region includes a first surface facing in a first direction, the multiplier region includes a second surface facing in the first direction, and the first surface has a larger area than the second surface.

11-48. (canceled)

19. The avalanche photodiode detector of claim 1, further comprising three insulating layers electrically isolating the absorber region from the semiconductor substrate.

20. An avalanche photodiode detector, comprising:

an absorber region formed over a semiconductor substrate and having an absorption layer for receiving incident photons and generating charged carriers; and  
a multiplier region formed over the semiconductor substrate and having a multiplication layer;

wherein the multiplier region is on a mesa structure separate from the absorber region and is coupled to the absorber region by a bridge, for transferring charged carriers from the absorber region to the multiplier region; and

further wherein the absorber region includes a first surface facing in a first direction, the multiplier region includes a second surface facing in the first direction, and the first surface has a larger area than the second surface.

21. The avalanche photodiode detector of claim 19, wherein the absorber region further includes a pair of first contacts.

22. The avalanche photodiode detector of claim 20, wherein bias across the absorber region is maintained by the first contacts.

23. The avalanche photodiode detector of claim 19, wherein the multiplier region further includes a pair of second contacts.

24. The avalanche photodiode detector of claim 22, wherein bias across the multiplier region is maintained by the second contacts.

25. The avalanche photodiode detector of claim 19, wherein the absorber region and the multiplier region are formed over a semiconductor substrate layer.

26. The avalanche photodiode detector of claim 19, wherein a Schottky junction is used for injecting carriers in the multiplication layer.

27. The avalanche photodiode detector of claim 19, wherein a quantum well and an N-well is used for injecting carriers in the multiplication layer.

28. The avalanche photodiode detector of claim 19, wherein the bridge is a metal bridge.

29. The avalanche photodiode detector of claim 19, further comprising at least one insulating layer electrically isolating the absorber region from the semiconductor substrate.

30. The avalanche photodiode detector of claim 29, further comprising three insulating layers electrically isolating the absorber region from the semiconductor substrate.

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