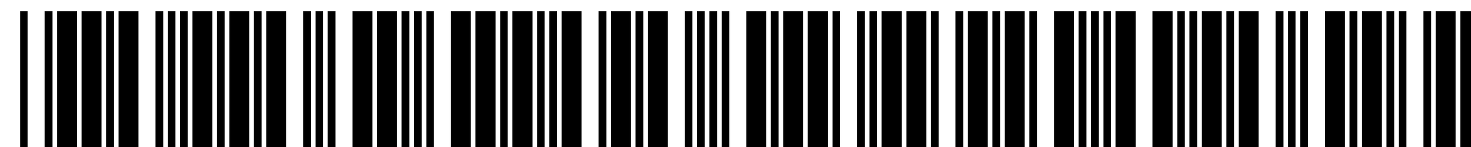

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(54) **PROCESS FOR MANUFACTURING HIGH-SENSITIVITY ACCELEROMETRIC AND GYROSCOPIC INTEGRATED SENSORS, AND SENSOR THUS PRODUCED**

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Appl. No.: **09/126,625**
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G01P 9/04 (2006.01)

(52) **U.S. Cl.** **73/514.32**; 73/504.12

(58) **Field of Classification Search** 73/514.32, 73/514.29, 514.36, 514.38, 514.17, 504.12, 73/504.14, 504.18

See application file for complete search history.

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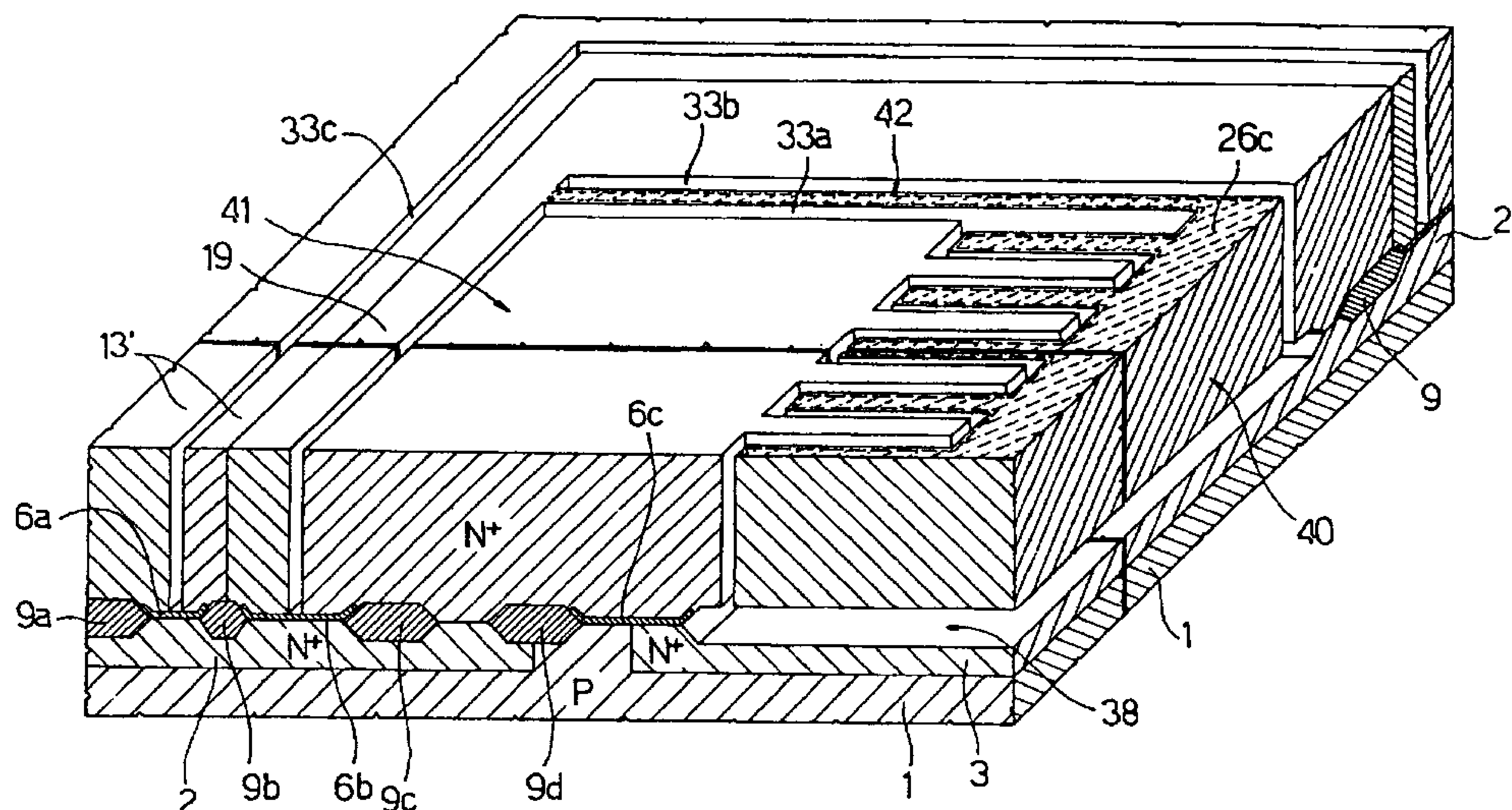
Primary Examiner—Helen C. Kwok
(74) *Attorney, Agent, or Firm*—David V. Carlson; Lisa K. Jorgenson

(57) **ABSTRACT**

A movable mass forming a seismic mass is formed starting from an epitaxial layer and is covered by a weighting region of tungsten which has high density. To manufacture the mass, buried conductive regions are formed in the substrate. Then, at the same time, a sacrificial region is formed in the zone where the movable mass is to be formed and oxide insulating regions are formed on the buried conductive regions so as to partially cover them. An epitaxial layer is then grown, using a nucleus region. A tungsten layer is deposited and defined and, using a silicon carbide layer as mask, the suspended structure is defined. Finally, the sacrificial region is removed, forming an air gap.

25 Claims, 5 Drawing Sheets



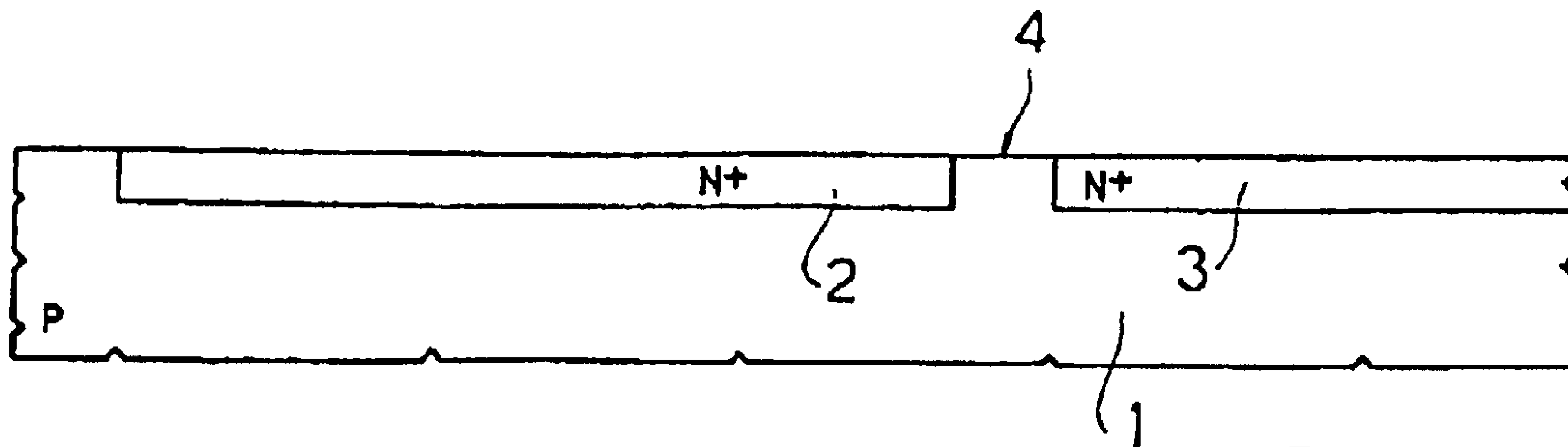


Fig.1

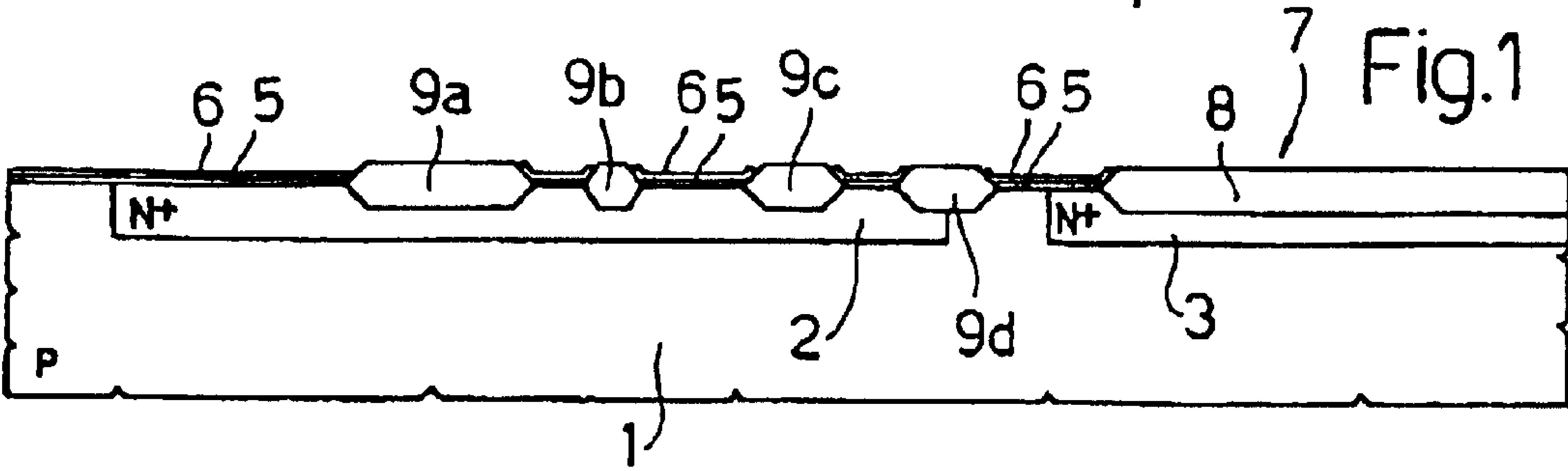


Fig.2

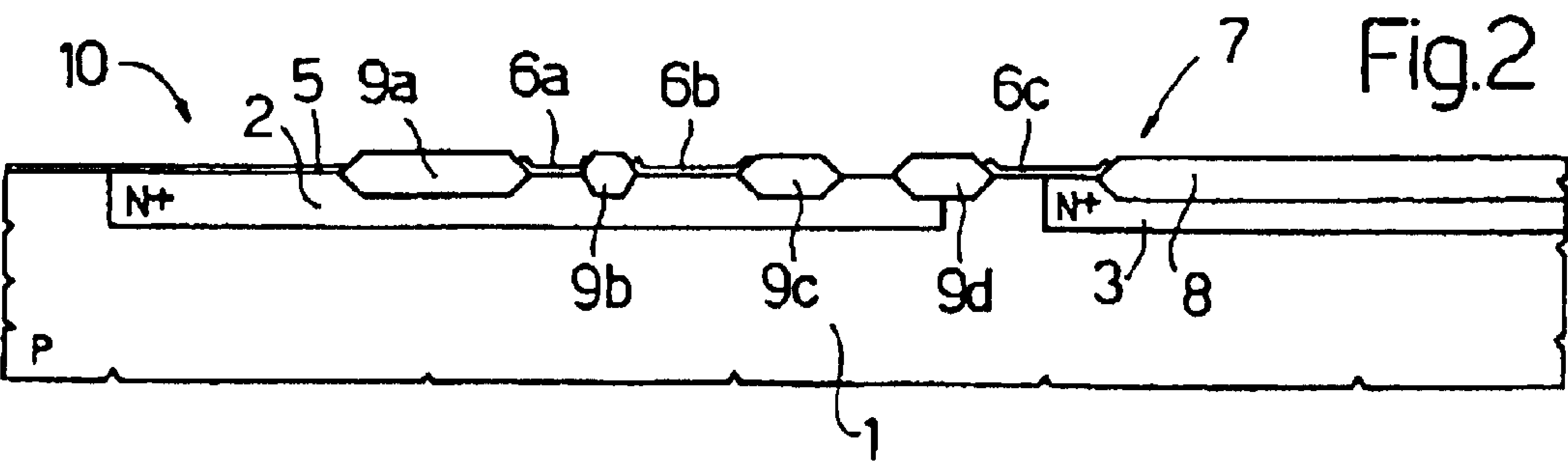


Fig.3

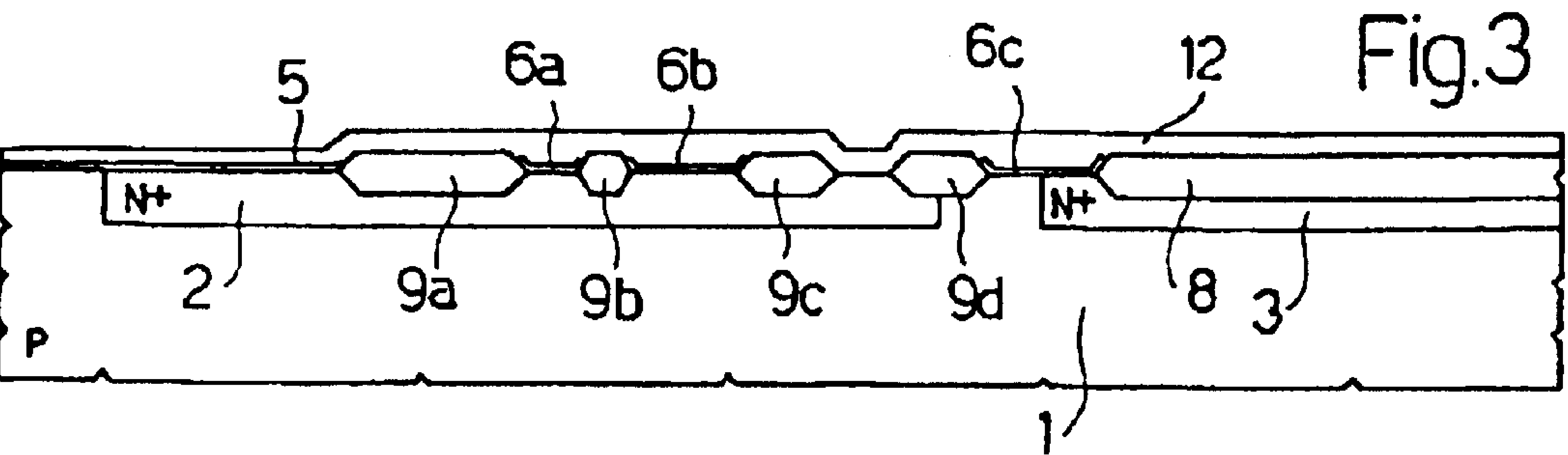


Fig.4

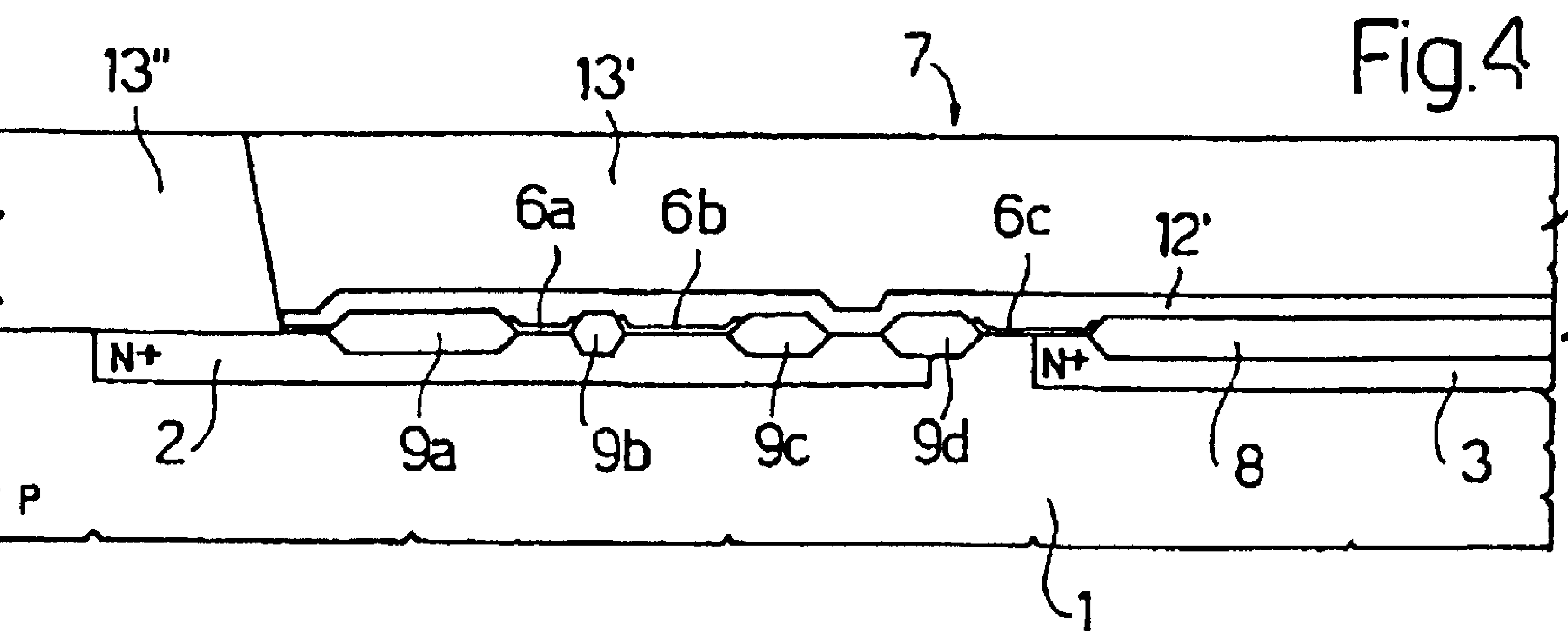


Fig.5

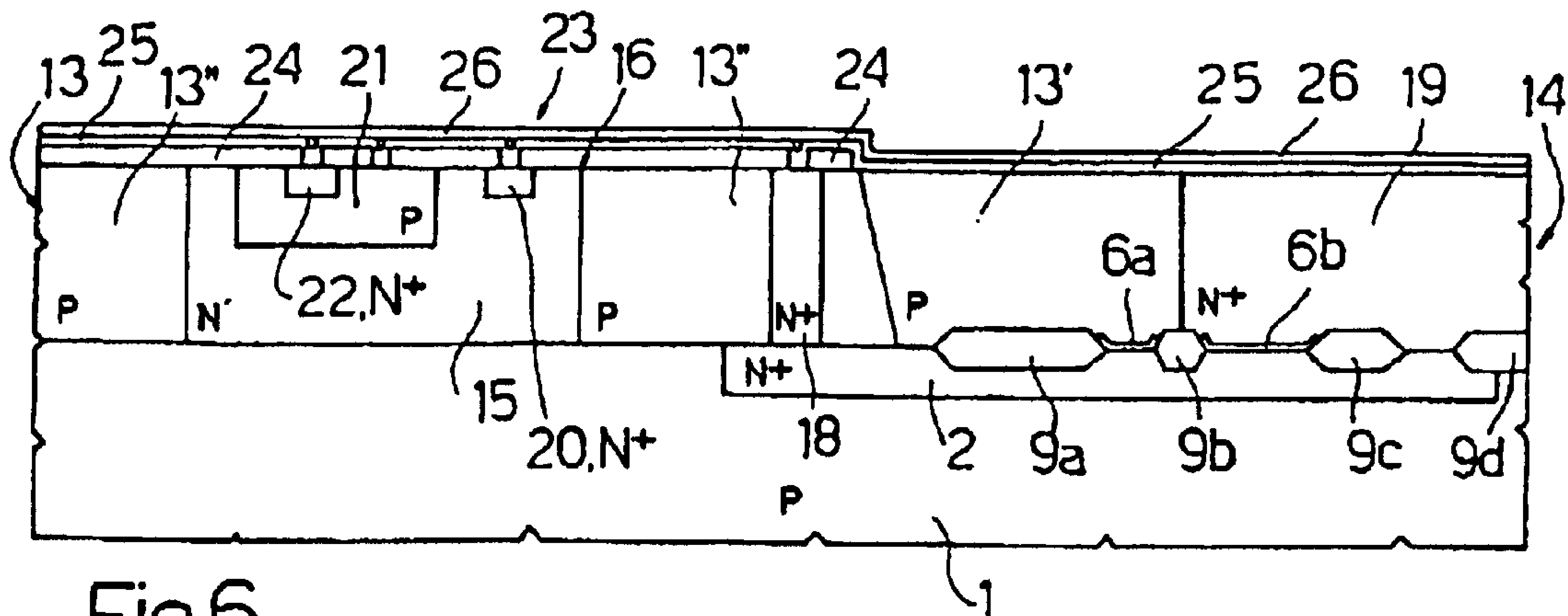


Fig.6

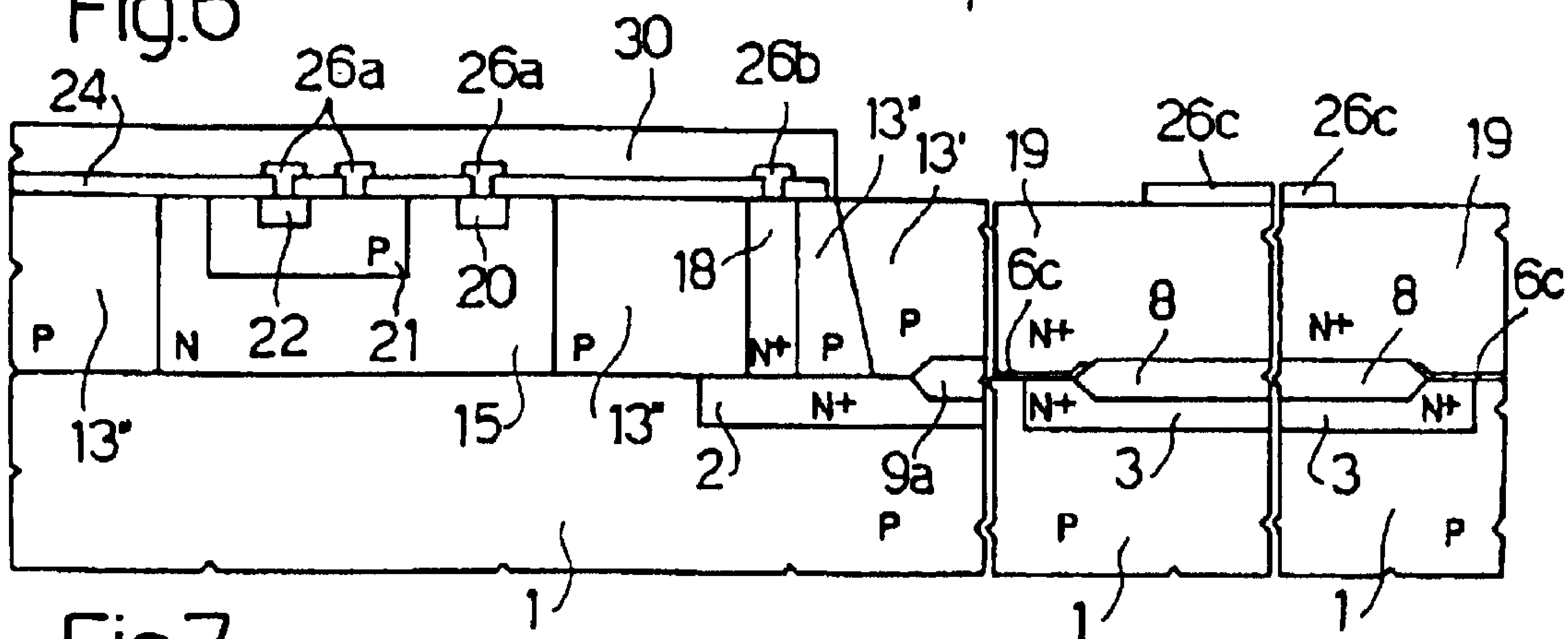


Fig.7

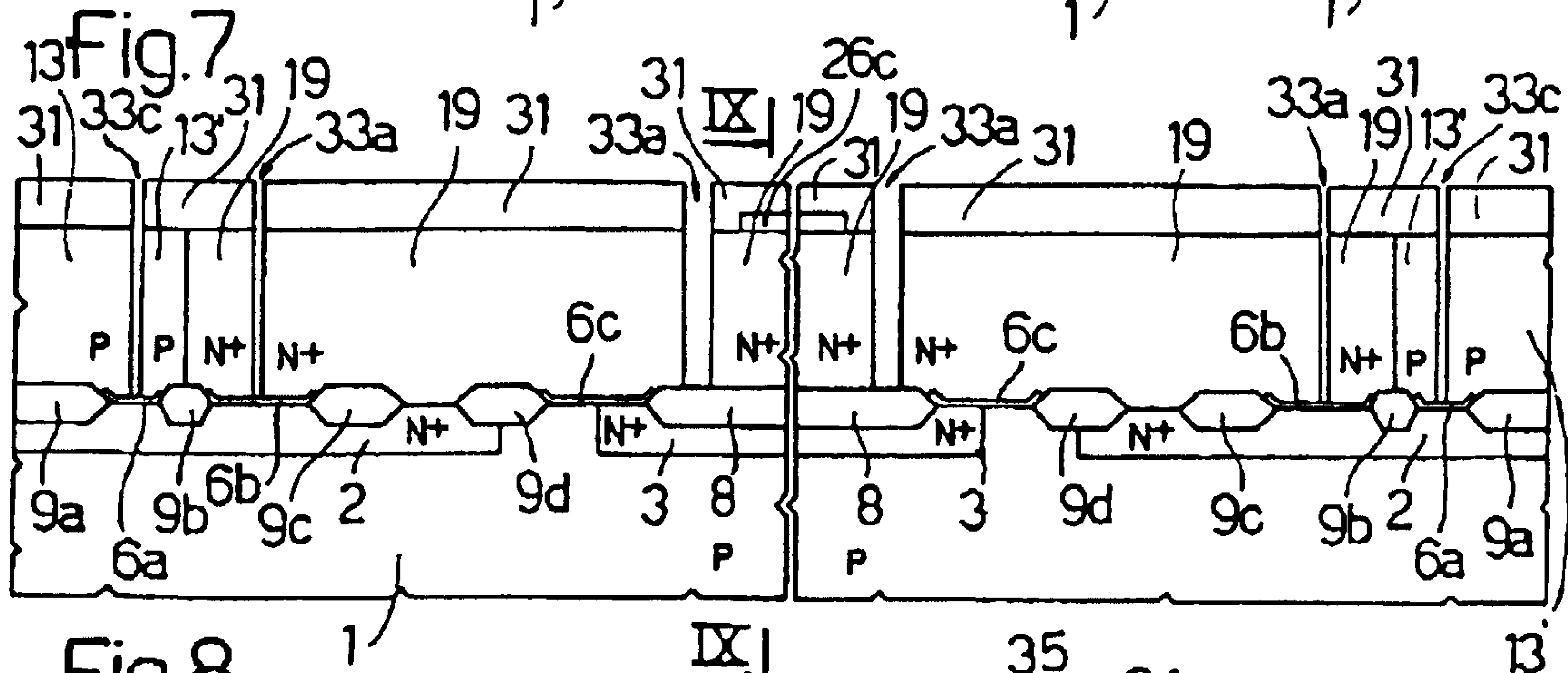


Fig.8

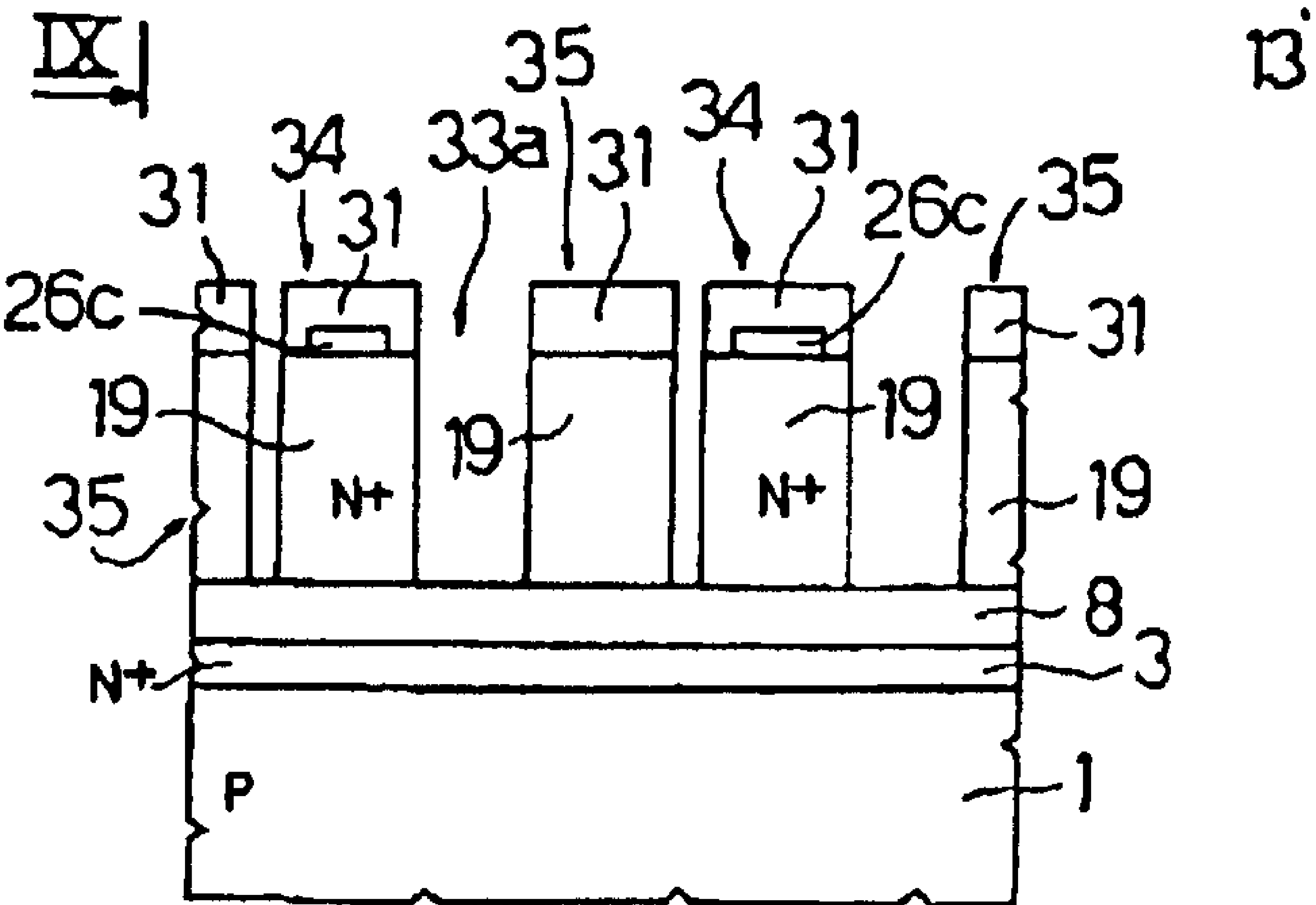


Fig.9

Fig.10

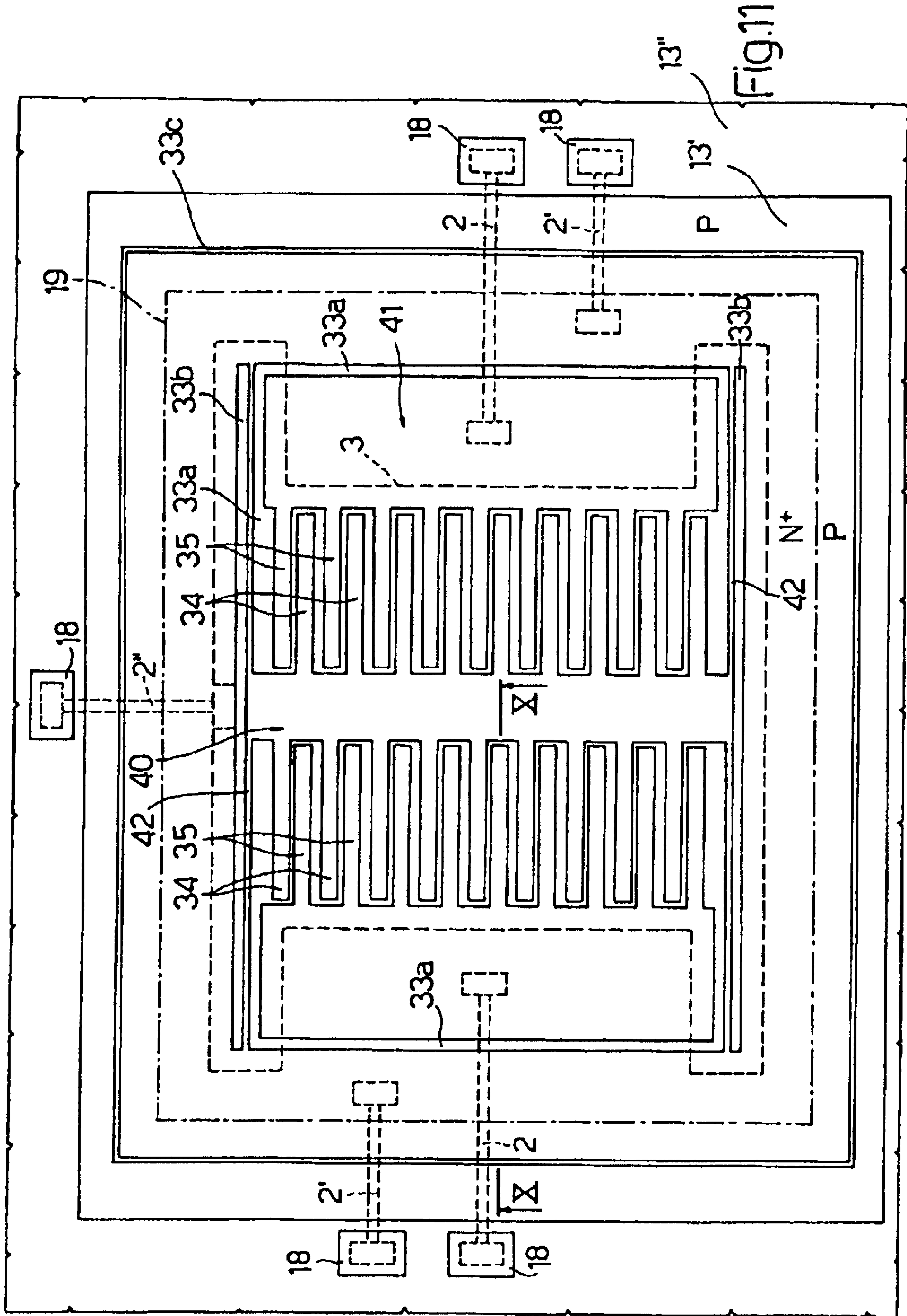


Fig.11
13"
13'
18
18
18
18
18
33c
19
2
2'
2
2'
2"
P
P
N+
33a
33b
33a
41
3
35
34
42
40
42
35
34
33a
XI
XI

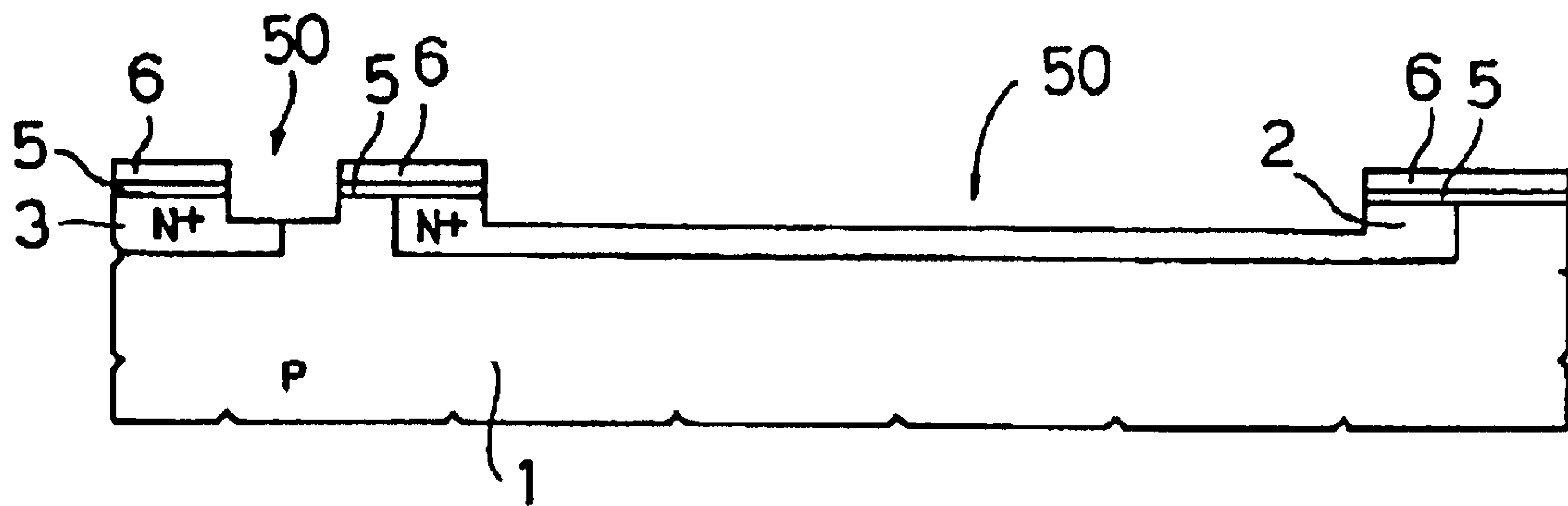


Fig. 12

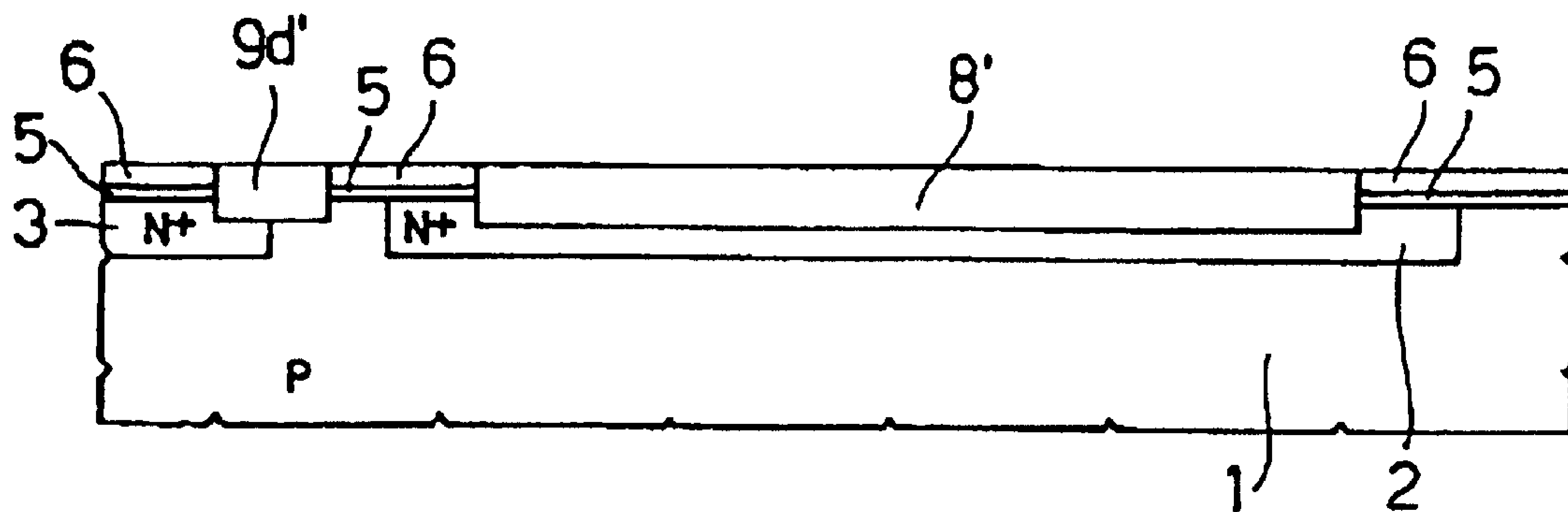


Fig. 13

PROCESS FOR MANUFACTURING HIGH-SENSITIVITY ACCELEROMETRIC AND GYROSCOPIC INTEGRATED SENSORS, AND SENSOR THUS PRODUCED

Matter enclosed in heavy brackets [ ] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue.

TECHNICAL FIELD

The invention relates to a process for manufacturing high-sensitivity accelerometric and gyroscopic integrated sensors and a sensor thus produced.

BACKGROUND OF THE INVENTION

As is known, using electromechanical microstructures of semiconductor material, the manufacture of which utilizes microelectronics techniques, has recently been proposed for producing accelerometers and gyroscopes. These silicon micro-machining techniques make it possible to produce different types of angular velocity and acceleration sensors. In particular, at the present time prototypes operating according to the piezoelectric, piezoresistive, capacitive, threshold, resonant and tunnel effect principles have been proposed.

Reference will be made below to an accelerometric sensor of differential capacitive type, i.e. one in which acceleration induces the movement of a seismic mass which constitutes the electrode common to two coupled capacitors by varying the two capacitances in opposite directions. This effect is known as differential variation of capacitance.

Historically, integrated micro-structures have been manufactured by preferably using the “bulk micro-machining” technique in which a wafer of single-crystal silicon is machined on both faces. This technique is, however, incompatible with the process steps for producing components of a circuit which processes a signal picked up by a sensitive element, as required at present.

It has been proposed to use the technique of “surface micro-machining” in which the sensitive element is made of multi-crystal silicon and suspended structures are formed by depositing and successively removing sacrificial layers. This technique is compatible with the current integrated circuit manufacturing processes and is therefore preferred at present. The integrated micro-structures produced with this technique are, however, relatively insensitive to acceleration and angular velocity. In fact, having a mass of the order of a few tenths of a microgram, they suffer the effects of thermodynamic noise caused by the Brownian movement of the particles of the fluid in which they are immersed (see, for example, the article by T. B. Gabrielson entitled “Mechanical-Thermal Noise in Micromachined Acoustic and Vibration Sensors“, IEEE Transactions on Electron Devices, vol. 40, No. 5, May 1993). The upper limit to the mass obtainable with these structures is imposed by genuinely technological reasons; the deposition of very thick films involves extremely long wafer machining times and renders the surface of the wafer unsuitable for the successive operations such as lapping the wafers.

A technique for machining the epitaxial layer (epitaxial micro-machining) is also known, which produces micro-structures with inertial masses that are higher and hence more sensitive, but not yet at a sufficient value for practical applications.

SUMMARY OF THE INVENTION

An object of the invention is to improve a process for manufacturing an accelerometric and gyroscopic sensor according to a technique of “epitaxial micro-machining” so as to increase its sensitivity further than the prior art.

An embodiment of the invention provides a process for manufacturing a high-sensitivity accelerometric and gyroscopic integrated sensor including forming a sacrificial region on a substrate of semiconductor material, growing an epitaxial layer that includes tungsten on the substrate and the sacrificial region, and then removing selective portions of the epitaxial layer and the sacrificial region to form a movable mass. The moveable mass formed is surrounded at the sides and separated from fixed regions by trenches, and separated from the substrate by an air gap.

It also provides for an accelerometric integrated sensor, having a substrate and an epitaxial layer of semiconductor material, whereby the epitaxial layer includes tungsten and forms a movable mass which is surrounded at sides by a fixed mass. The movable mass is separated from the substrate by a gap from below and from the fixed mass by trenches at the sides, and is supported by the fixed mass through anchorage portions.

BRIEF DESCRIPTION OF THE DRAWINGS

For an understanding of the invention, a number of preferred embodiments will now be described, purely by way of non-exhaustive example, with reference to the accompanying drawings.

FIGS. **1**–**8** show cross sectional views at different points of a semiconductor wafer during successive steps of the manufacturing process according to the invention.

FIG. **9** shows a cross sectional view of a plane perpendicular to FIG. **8**.

FIG. **10** shows a perspective view of the sensor obtained with the process of FIGS. **1**–**9**.

FIG. **11** shows a top view of the sensor of FIG. **10**.

FIGS. **12** and **13** show transverse sections of a portion of a wafer in two successive manufacturing steps according to a different embodiment of the process.

DETAILED DESCRIPTION

An embodiment of a capacitive-type accelerometric or gyroscopic sensor according to a first embodiment of the process will now be described with reference to FIGS. **1**–**10**, in which the thicknesses of the various layers of material are not to scale and some layers are not shown in all the illustrations for reasons of representation.

Shown in FIG. **1**, buried N^+-type conductive regions **2**, **3** to form buried interconnections are formed in a substrate **1** of single-crystal silicon of P-type conductivity, using conventional masking and implantation techniques. A pad oxide layer **5** is formed, e.g., grown thermally, on a surface **4** of the substrate **1**, and a silicon nitride layer **6** is deposited on it. The silicon nitride layer **6** is then defined and removed selectively in a sensor zone **7**. Then the portions of the surface of the substrate **1** not covered by the layer **6** are locally oxidated, forming oxide regions comprising a sacrificial region **8** (surrounded at the sides and underneath by the buried conductive region **3**) and buried oxide regions **9**a, **9**b, **9**c and **9**d at the buried conductive region **2**, obtaining the structure of FIG. **2**.

Through suitable masking steps, portions of the layers **5**, **6** are then removed in the sensor zone **7** where the buried contacts of the sensor and of the silicon nitride layer **6** are to be formed in the circuitry and from an interconnection area **10**, obtaining the structure of FIG. **3**. In FIG. **3**, the pad oxide layer **5** underneath the silicon nitride layer **6** is not shown

and **6**a, **6**b and **6**c denote the portions of nitride included, respectively, between the buried oxide regions **9**a and **9**b; **9**b and **9**c and the regions **9**d and **8**.

An amorphous or multi-crystal silicon layer **12** is then deposited, as shown in FIG. **4**. By means of a phototechnique and plasma etching step, the amorphous or multi-crystal silicon layer **12** is removed, except in the sensor zone **7**, forming a silicon region **12'** representing the nucleus for a successive epitaxial growth step. By means of chemical etching, the pad oxide layer **5** is then removed where exposed and epitaxial growth takes place with formation of a "pseudo-epitaxial", P-type layer **13**. In the sensor zone **7**, the layer **13** has a multi-crystal structure (multi-crystal region **13'**) and a single-crystal structure elsewhere (single-crystal region **13"**). A wafer **14** as shown in FIG. **5** is thus obtained.

The pseudo-epitaxial layer **13** is then doped with doping ions suitable for determining an N-type conductivity to form deep regions. In particular, as shown in FIG. **6**, in which a portion of the wafer **14** is shown slightly displaced to the left with respect to FIGS. **1**–**5**, a deep N^+-type region **18** is formed in the single-crystal region **13"** and extends from a surface **16** as far as the buried conductive region **2**. This deep region **18** electrically connects the buried conductive region **2** to the surface **16**. Also formed in the multi-crystal region **13'** is an N^+-type well **19** that extends from the surface **16** as far as the buried conductive region **3** (see FIG. **7**) and, partially, the buried conductive region **2**. In particular, the well **19** extends above the buried oxide regions **9**c, **9**d and half of the buried oxide region **9**b, electrically contacting the buried conductive region **2** in the area included between the buried oxide regions **9**c and **9**d that are not covered by the portions of nitride **6**a–**6**c.

The electronic components of the circuitry are then formed by means of standard steps. In the example shown, an N-type collector well **15** is formed, extending from the surface **16** of the pseudo-epitaxial layer **13** as far as the substrate **1**. An NPN transistor **23**, having an N^+-type collector contact region **20**, a P-type base region **21** and an N^+-type emitter region **22** is formed in the collector well **15**.

A dielectric layer **24** for opening the contacts, e.g., BPSG (boron phosphorus silicon glass) is then deposited on the surface **16** of the wafer **14**. Then, by a suitable masking and selective removal step, the contacts are opened in the circuitry area and on the deep region **18**, and a part of the dielectric layer **24** is removed from the sensor zone **7**. An adhesive layer **25** (of titanium nitride for example) is then deposited, to facilitate the adhesion of the next layer to the silicon of the wafer **14**. A tungsten layer **26** is deposited by CVD (Chemical Vapor Deposition) at a thickness of 1 μm thick, for example, obtaining the intermediate structure of FIG. **6**. The nucleus silicon region **12'** has been omitted in FIG. **6**.

The tungsten layer **26** is then shaped, by means of known photolithographic steps, so as to form contacts **26**a of the circuitry and **26**b of the sensor and a weighting region **26**c over the well **19**, as shown in FIG. **7** in which the adhesive layer **25** is not shown. In particular, the weighting region **26**c is shaped as partially shown in FIG. **10**, i.e., corresponding to the shape of the movable electrode of the sensor, as explained in greater detail below. A dielectric passivation layer **30** is then deposited and this is removed in the zone of the contact pads (to permit the electrical contacting of the device, in a manner not shown), and in the sensor zone **7**, thus obtaining the structure of FIG. **7**.

A silicon carbide layer **31**, intended to form a mask for the subsequent step of excavation of the pseudo-epitaxial layer

13 and precisely of the multi-crystal region **13'**, is then deposited and defined. Excavations are carried out to release the movable mass of the accelerometer, to separate the fixed and movable electrodes and to insulate the regions at different potential. Thus a trench **33**a which separates the fixed part from the movable part and the fixed mass from the surrounding portion of the well **19** is formed. A trench **33**b (see FIGS. **10** and **11**) separating the anchorage regions from the surrounding portion of the well **19** and a trench **33**c separating the sensor from the rest of the chip are also formed. The structure is thus obtained which is shown in FIG. **8**, taken on the same section as FIGS. **1**–**7** but centred on the sensor zone **7**, and in FIG. **9**, taken perpendicular to that of FIG. **8**. FIG. **9** shows transverse walls **34** and **35** defining the movable electrodes and the fixed electrodes of the sensor, as explained in greater detail below with reference to FIGS. **10** and **11**.

Finally, the sacrificial region **8** is removed by etching in, e.g., hydrofluoric acid, and the zone previously occupied by this region **8** forms an air gap **38** which at the bottom separates the movable mass from the rest of the wafer. The movable mass is then etched and supported by the chip only at the anchorage zones. With a subsequent etching in plasma, the silicon carbide layer **31** is removed from all areas of the wafer. The final structure is thus obtained which is shown in FIGS. **10** and **11** in which the movable mass is denoted by **40**, the fixed mass by **41**, and the anchorage zones of the movable mass by **42**. In particular, FIG. **11** shows the outer edge of the buried conductive region **3** in broken lines and the outer edge of the well **19** in dot-and-dash lines. Broken lines also denote the buried conductive regions **2** for forming the buried connections of the fixed mass, and **2'**, **2"** those of the movable mass, formed at the same time and in the same way as the buried conductive region **2**. FIG. **10** also shows the profile of the weighting region **26**c.

As will be noted, the movable mass **40** is H-shaped and the transverse walls **34** define the movable electrodes of the capacitive sensor. The moveable electrodes are interleaved in a comb-like manner with the transverse walls **35** defining the fixed electrodes and are separated from its central element. The structure is therefore equivalent to a capacitor formed by two capacitors in series, each formed by a plurality of elementary capacitors connected in parallel.

In per se known manner, through the deep regions **18** and the buried conductive regions **2**, **2'**, **2"**, and **3**, the movable electrodes **34** and the fixed electrodes **35** are biased at different voltages so that when the movable mass **40** is subjected to acceleration, the consequent change of distance between the movable electrodes and the fixed ones may be detected as a variation of capacitance.

Manufacturing the movable mass **40** in a semiconductor material having a tungsten weighting region **26**c, as described, gives the sensor high sensitivity. In fact, tungsten has high density (19.3 g/cm3) with respect to multi-crystal or amorphous silicon (2.33 g/cm3). Consequently, a tungsten layer 1 μm thick is virtually equivalent, from the point of view of the mechanical properties, to a 10 μm polysilicon layer. On the other hand, the deposition by CVD of a tungsten layer of the indicated thickness can easily be achieved with the conventional integrated microelectronics machining techniques.

The sensor obtained in this way thus has high sensitivity, yet benefits from the advantages typical of epitaxial machining technology and permits the integration of the sensor together with the integrated signal processing circuit.

The manufacturing process is simple to implement, using steps typical of microelectronics and forms the metallic cir-

cuit interconnection regions and the weighting regions of the movable structure at the same time. The process is also readily controllable and repeatable.

According to a different embodiment of the invention, the buried oxide regions **8** and **9** are grown in recesses previously formed in the substrate **1**, after the buried conductive regions **2**, **3** have been formed. In detail, shown in FIG. **12**, starting from the structure of FIG. **1**, the oxide **5** and nitride **6** layers are formed and defined in a similar manner to that described with reference to FIG. **2**. The portions of substrate **1** not covered by the layers **5**, **6** are then etched, forming recesses **50** (FIG. **12**). The recesses **50** are then filled with thermally grown oxide regions, only the sacrificial region **8'** and the buried oxide region **9**d', shown in FIG. **13**. The further steps described above then follow, starting from the removal of portions of nitride **6** and of oxide **5** where the contacts are to be formed and in the zone of the circuitry, as described from FIG. **3** onwards.

According to a further embodiment which is not shown, the sacrificial and buried oxide regions may be obtained by depositing and shaping an oxide layer.

Finally it will be clear that numerous modifications and variations may be introduced to the process and sensor described and illustrated herein, all coming within the scope of the inventive concept as defined in the accompanying claims. In particular, the components of the circuitry integrated with the sensor may be either bipolar or MOS; the conductivity of the conductive regions may be the opposite of that shown and the protective and/or adhesive materials may be replaced by others which are equivalent as regards the functions desired, as well as other changes and variations.

What is claimed is:

1. An integrated sensor, comprising:

a substrate *of a first conductivity type* and an epitaxial layer of semiconductor material formed on said substrate, said epitaxial layer forming a movable mass [which] *that* is surrounded at *its* sides by a fixed mass;

said movable mass [being] separated from said substrate by a gap and at the sides from said fixed mass through trenches formed in said epitaxial layer;

said movable mass [being] supported by said fixed mass through anchorage portions in said epitaxial layer; [and]

buried conductive regions of second conductivity type formed in the substrate and providing electrical contact between the movable mass and the fixed mass, the buried conductive regions selectively facing the epitaxial layer; and

a weighting region [comprising tungsten] at said movable mass.

2. The sensor according to claim **1** wherein said weighting region extends above said movable mass.

3. The sensor according to claim **2** wherein said weighting region is surrounded by a protective layer of silicon carbide.

4. The sensor according to claim **2**, further comprising electronic components formed in a single-crystal epitaxial region in said epitaxial layer wherein said electronic components comprise tungsten contact electrodes.

5. The sensor according to claim **4** wherein adhesive titanium nitride regions extend underneath said weighting region and said contact electrodes.

6. The sensor of claim **1** [wherein said substrate has a first conductivity type, the sensor], further comprising:

[buried conductive regions of a second conductivity type extending in said substrate and selectively facing said epitaxial layer;]

electrically insulating material regions extending on said buried conductive regions and delimiting therebetween portions of selective contact between said buried conductive regions and said movable mass and said fixed mass; and

deep contact regions extending from a surface of said epitaxial layer as far as said buried conductive regions to form deep contacts.

7. The sensor of claim **1** wherein said movable mass has movable electrodes facing and interleaved with fixed electrodes extending from said fixed mass to form a sensor of capacitive type, said movable electrodes comprising respective tungsten weighting regions.

8. An integrated sensor comprising:

a semiconductor substrate having an epitaxial layer formed thereon;

a fixed mass formed in the epitaxial layer on the substrate; and

a movable mass formed in the epitaxial layer and suspended over the substrate to form a gap between the movable mass and the semiconductor substrate, the movable mass [including a tungsten layer and] being supported by the fixed mass through anchorage portions and separated from the fixed mass by trenches*;*

buried conductive regions of a second conductivity type extending in said substrate and selectively facing said epitaxial layer;

electrically insulating material regions extending on said buried conductive regions and delimiting therebetween portions of selective contact between said buried conductive regions and said movable mass and said fixed mass; and

a weighting region.

9. The sensor of claim **8** wherein the *movable mass includes a* tungsten layer [is] surrounded by a protective layer.

10. The sensor of claim **8**, further including electronic components formed on the fixed mass.

11. The sensor of claim **8** wherein the movable mass has moveable electrodes interleaved with fixed electrodes that extend from the fixed mass thus forming a capacitive sensor.

12. An integrated sensor, comprising:

a substrate having a first conductivity type and an epitaxial layer of semiconductor material, the epitaxial layer configured to have a movable mass surrounded at its sides by a fixed mass, the movable mass being separated from the substrate by a gap and separated at the sides from the fixed mass through trenches, the movable mass being supported by the fixed mass through anchorage portions in the epitaxial layer;

a weighting region [comprising tungsten] at the movable mass;

buried conductive regions of a second conductivity type extending in the substrate and selectively facing the epitaxial layer;

electrically insulating material regions extending on the buried conductive regions and delimiting therebetween portions of selective contact between the buried conductive regions and the movable mass and the fixed mass; and

deep contact regions extending from a surface of the epitaxial layer as far as the buried conductive regions to form deep contacts.

13. The sensor of claim **12** wherein the weighting region *comprises tungsten that* extends above the movable mass.

14. The sensor of claim **13** wherein the weighting region is surrounded by a protective layer of silicon carbide.

15. The sensor of claim **13**, further comprising electronic components formed in a single-crystal epitaxial region in the epitaxial layer, and the electronic components comprising tungsten contact electrodes.

16. The sensor of claim **15** wherein adhesive titanium nitride regions extend underneath the weighting region and the contact electrodes.

17. An integrated sensor, comprising:

a substrate of a first conductivity type and an epitaxial layer of semiconductor material formed on said substrate, said epitaxial layer forming a movable mass that is surrounded at its sides by a fixed mass;

said movable mass separated from said substrate by a gap and at the sides from said fixed mass through trenches formed in said epitaxial layer;

said movable mass supported by said fixed mass through anchorage portions in said epitaxial layer;

buried conductive regions of a second conductivity type extending in the substrate and selectively facing the epitaxial layer;

electrically insulating material regions extending on the buried conductive regions and delimiting therebetween portions of selective contact between the buried conductive regions and the movable mass and the fixed mass; and

a weighting region comprising a metal at said movable mass.

18. The integrated sensor of claim 17 wherein said weighting region comprises the metal layer formed on top of the fixed mass.

19. The integrated sensor of claim 17, the sensor further comprising:

deep contact regions extending from a surface of the epitaxial layer as far as the buried conductive regions to form deep contacts.

20. An integrated sensor, comprising:

a substrate having a first conductivity type and an epitaxial layer of semiconductor material formed on said substrate, said epitaxial layer forming a movable mass that is surrounded at its sides by a fixed mass;

said movable mass being separated from said substrate by a gap and at the sides from said fixed mass through trenches formed in said epitaxial layer;

said movable mass being supported by said fixed mass through anchorage portions in said epitaxial layer;

a weighting region at said movable mass;

buried conductive regions of a second conductivity type extending in said substrate and selectively facing said epitaxial layer;

electrically insulating material regions extending on said buried conductive regions and delimiting therebetween portions of selective contact between said buried conductive regions and said movable mass and said fixed mass; and

deep contact regions extending from a surface of said epitaxial layer as far as said buried conductive regions to form deep contacts.

21. The sensor according to claim 20 wherein said weighting region extends above said movable mass.

22. The sensor according to claim 21 wherein said weighting region is surrounded by a protective layer of silicon carbide.

23. The sensor according to claim 21, further comprising electronic components formed in a single-crystal epitaxial region in said epitaxial layer wherein said electronic components comprise tungsten contact electrodes.

24. The sensor according to claim 23 wherein adhesive titanium nitride regions extend underneath said weighting region and said contact electrodes.

25. The sensor of claim 20 wherein said movable mass has movable electrodes facing and interleaved with fixed electrodes extending from said fixed mass to form a sensor of capacitive type, said movable electrodes comprising respective tungsten weighting regions.

* * * * *