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(54) **FABRICATION OF NANO-SHEET TRANSISTORS WITH DIFFERENT THRESHOLD VOLTAGES**

(58) **Field of Classification Search**
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(Continued)

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Filed: **Mar. 17, 2017**

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H01L 21/02 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC **H01L 29/0673** (2013.01); **H01L 27/088** (2013.01); **H01L 21/02603** (2013.01);
(Continued)

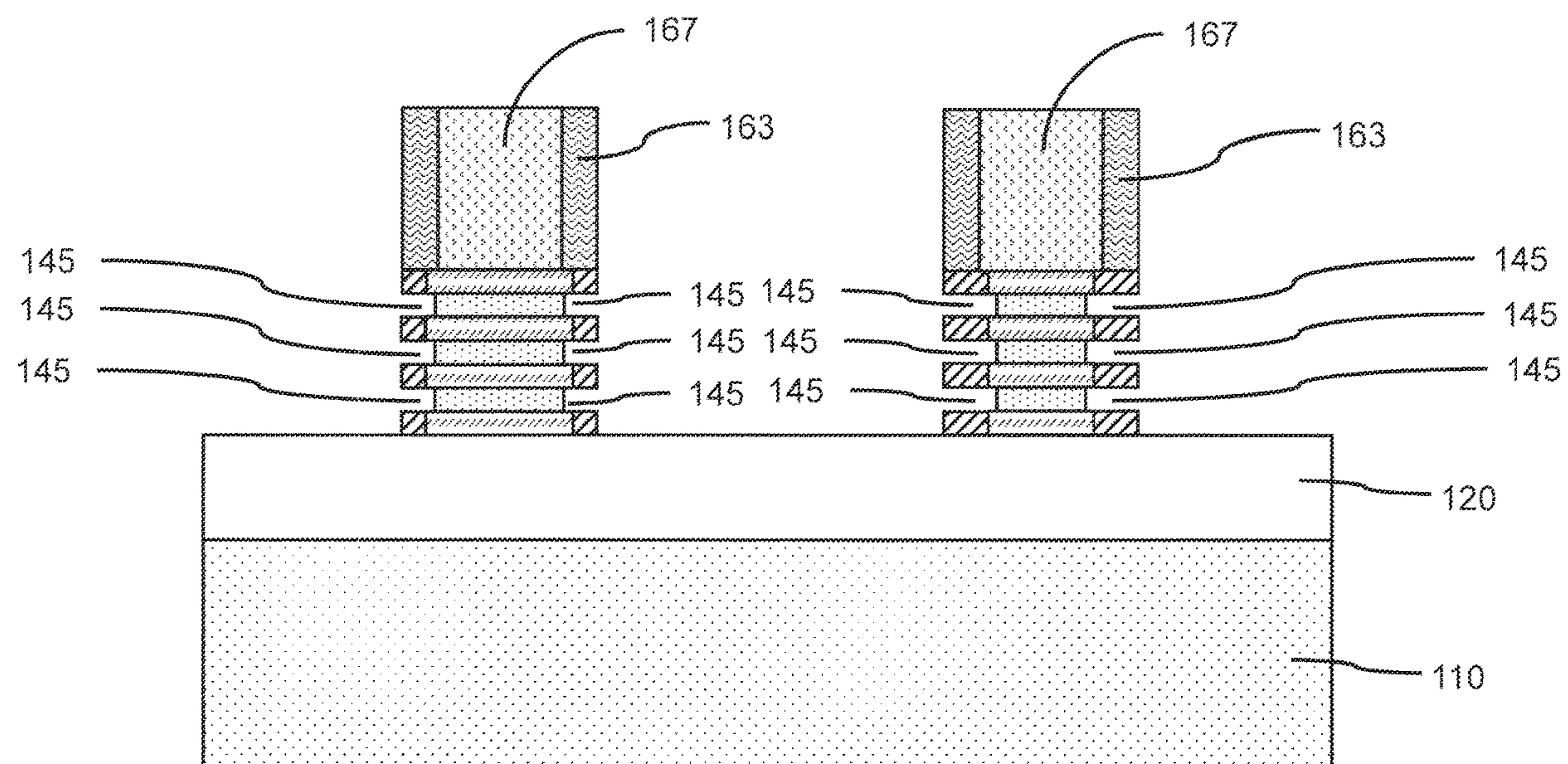
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(57) **ABSTRACT**

A method of forming two or more nano-sheet devices with varying electrical gate lengths, including, forming at least two cut-stacks including a plurality of sacrificial release layers and at least one alternating nano-sheet channel layer on a substrate, removing a portion of the plurality of sacrificial release layers to form indentations having an indentation depth in the plurality of sacrificial release layers, and removing a portion of the at least one alternating nano-sheet channel layer to form a recess having a recess depth in the at least one alternating nano-sheet channel layers, where the recess depth is greater than the indentation depth.

41 Claims, 19 Drawing Sheets



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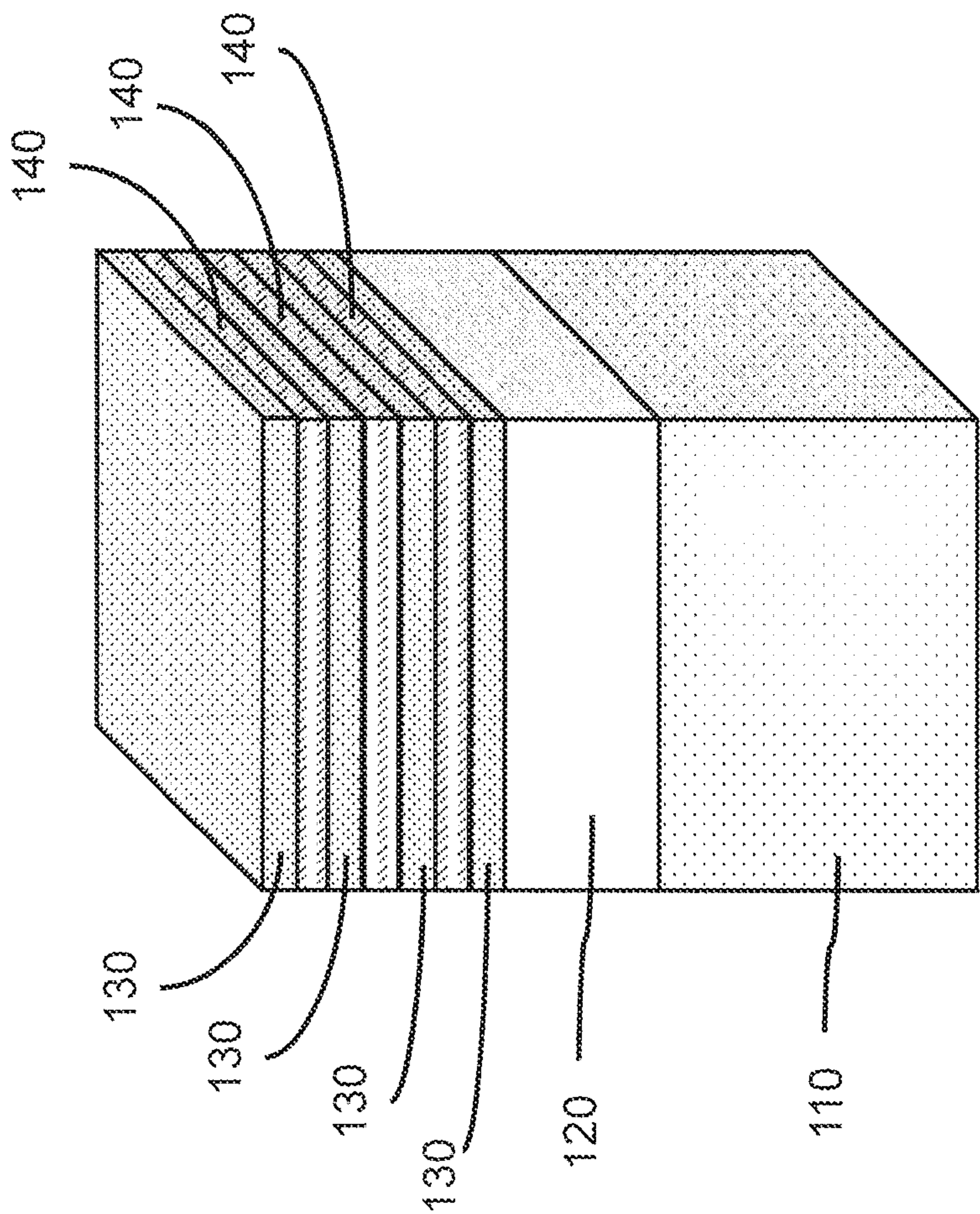


FIG. 1

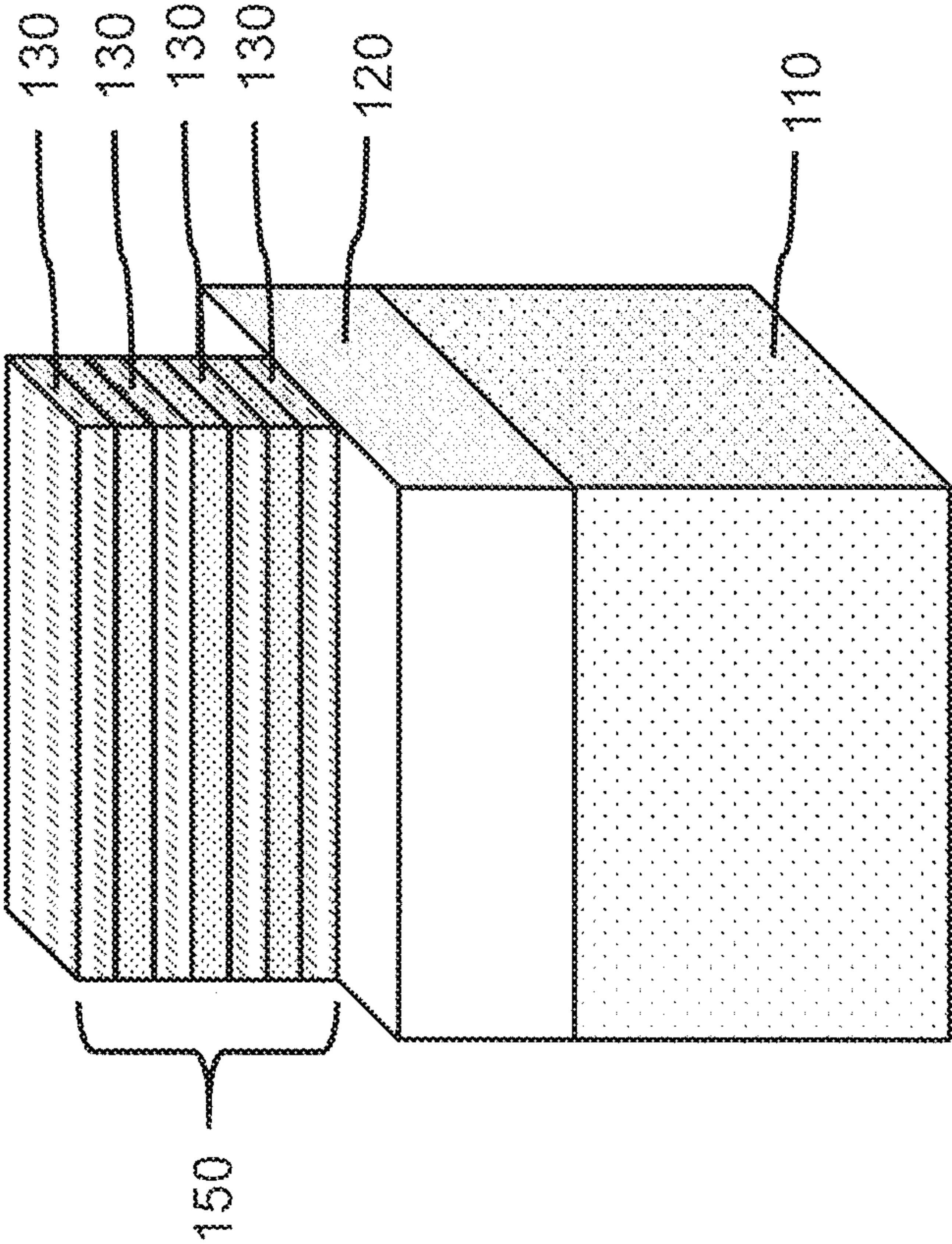


FIG. 2

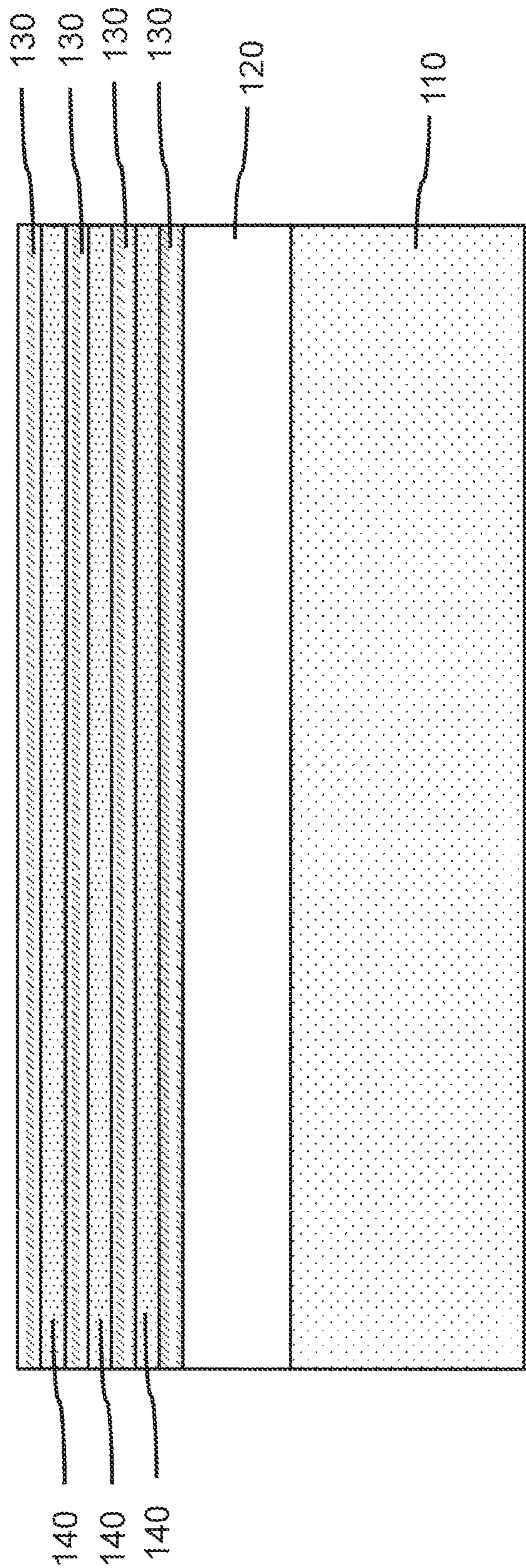


FIG. 3

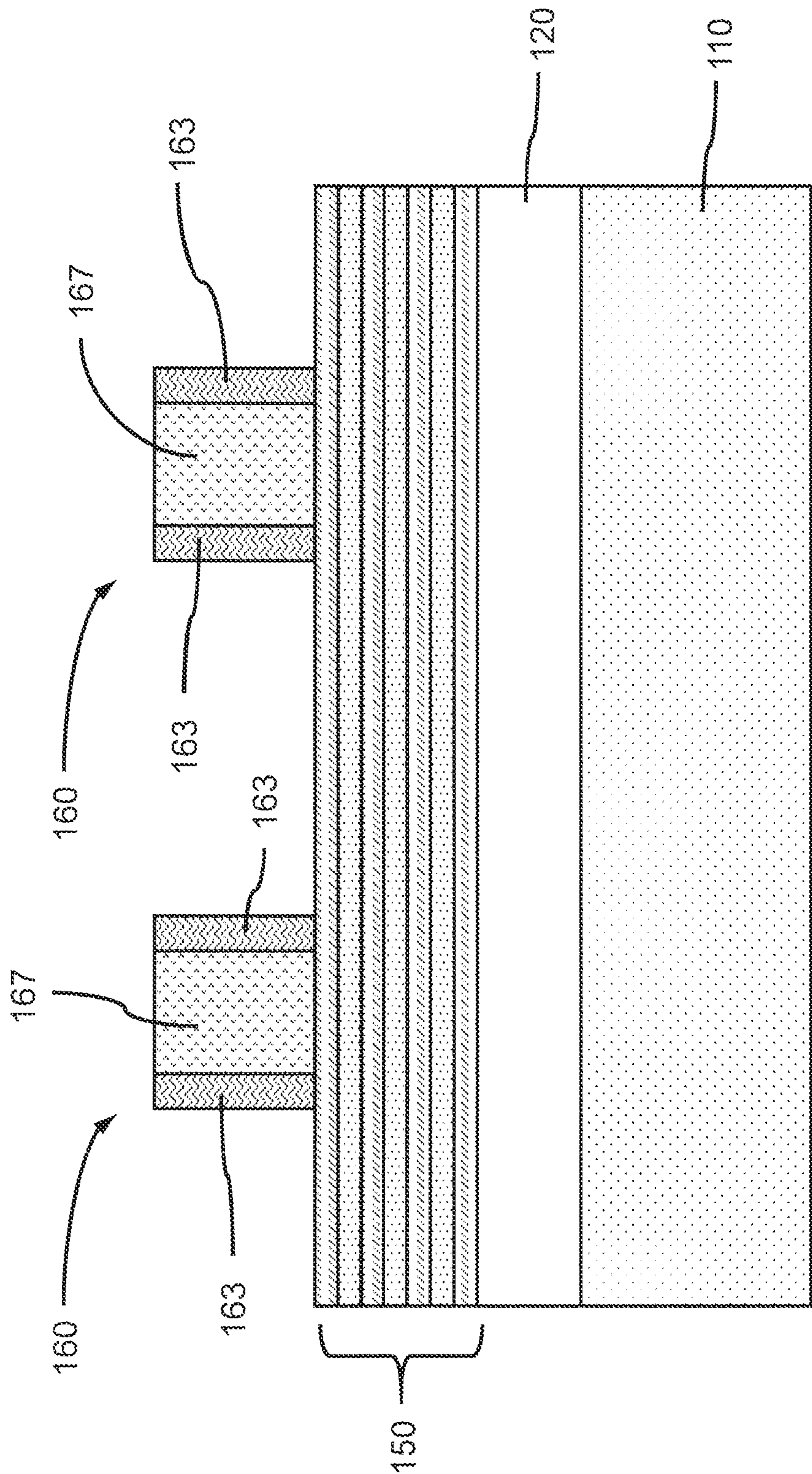
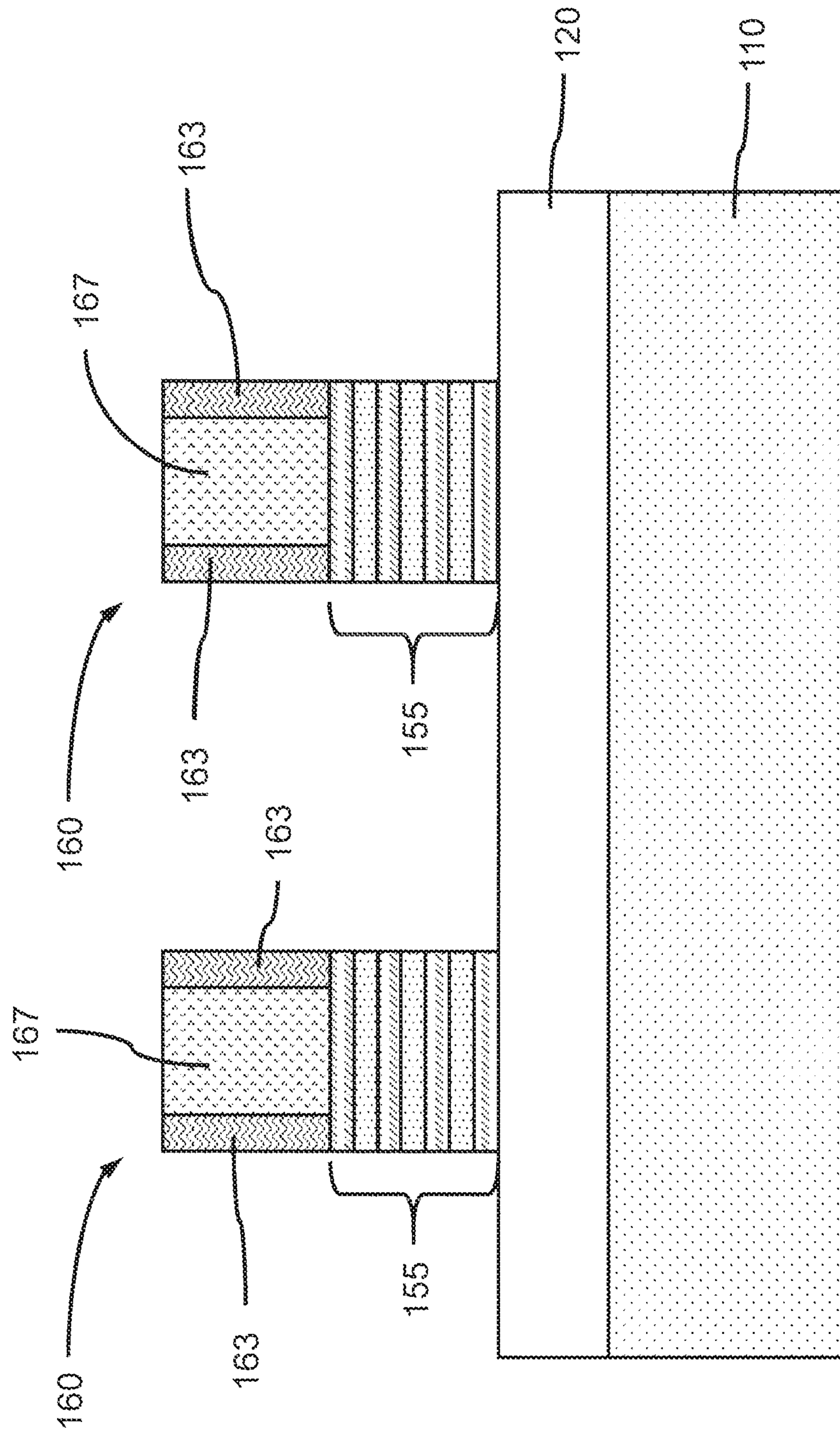


FIG. 4



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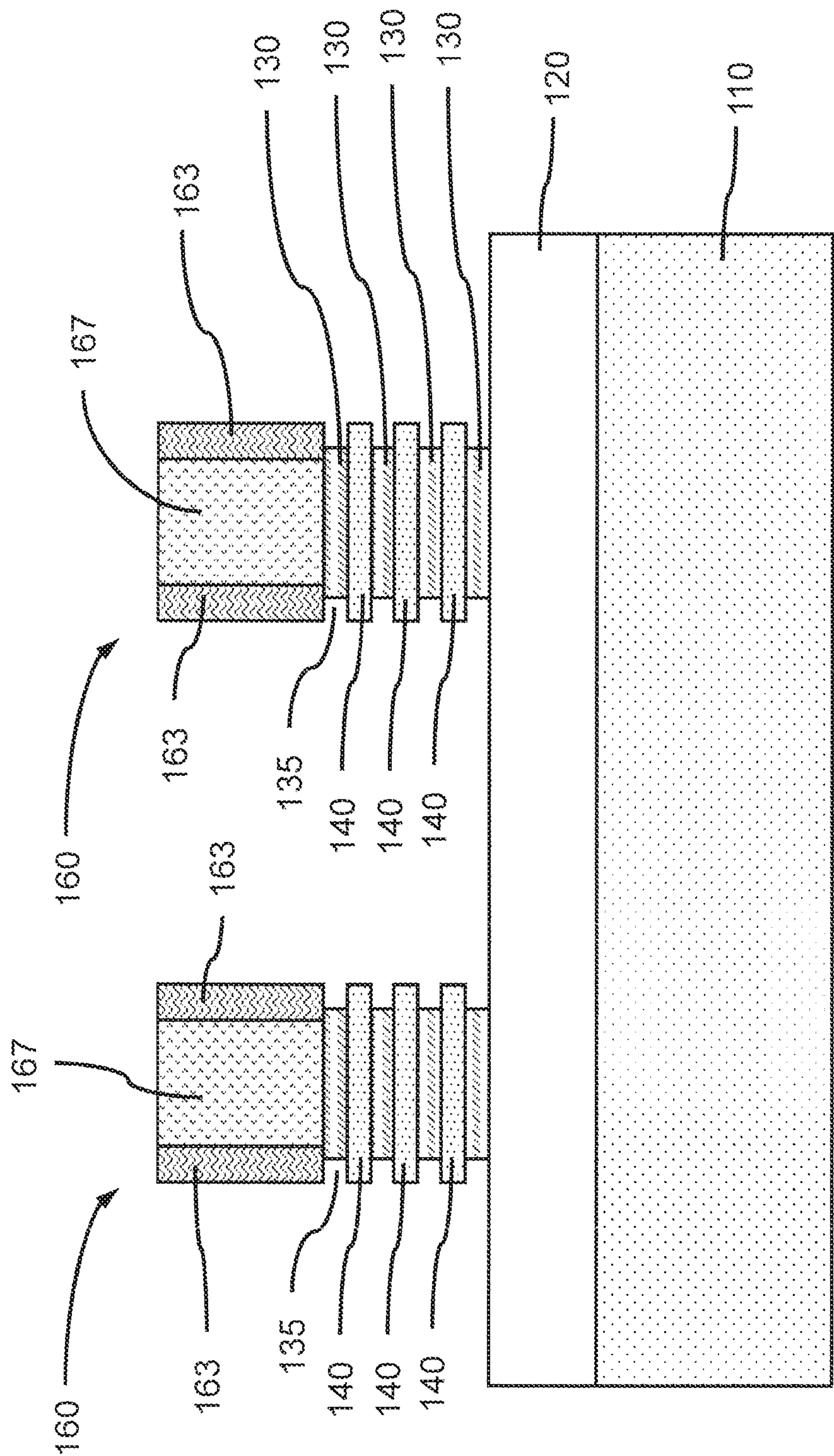


FIG. 6

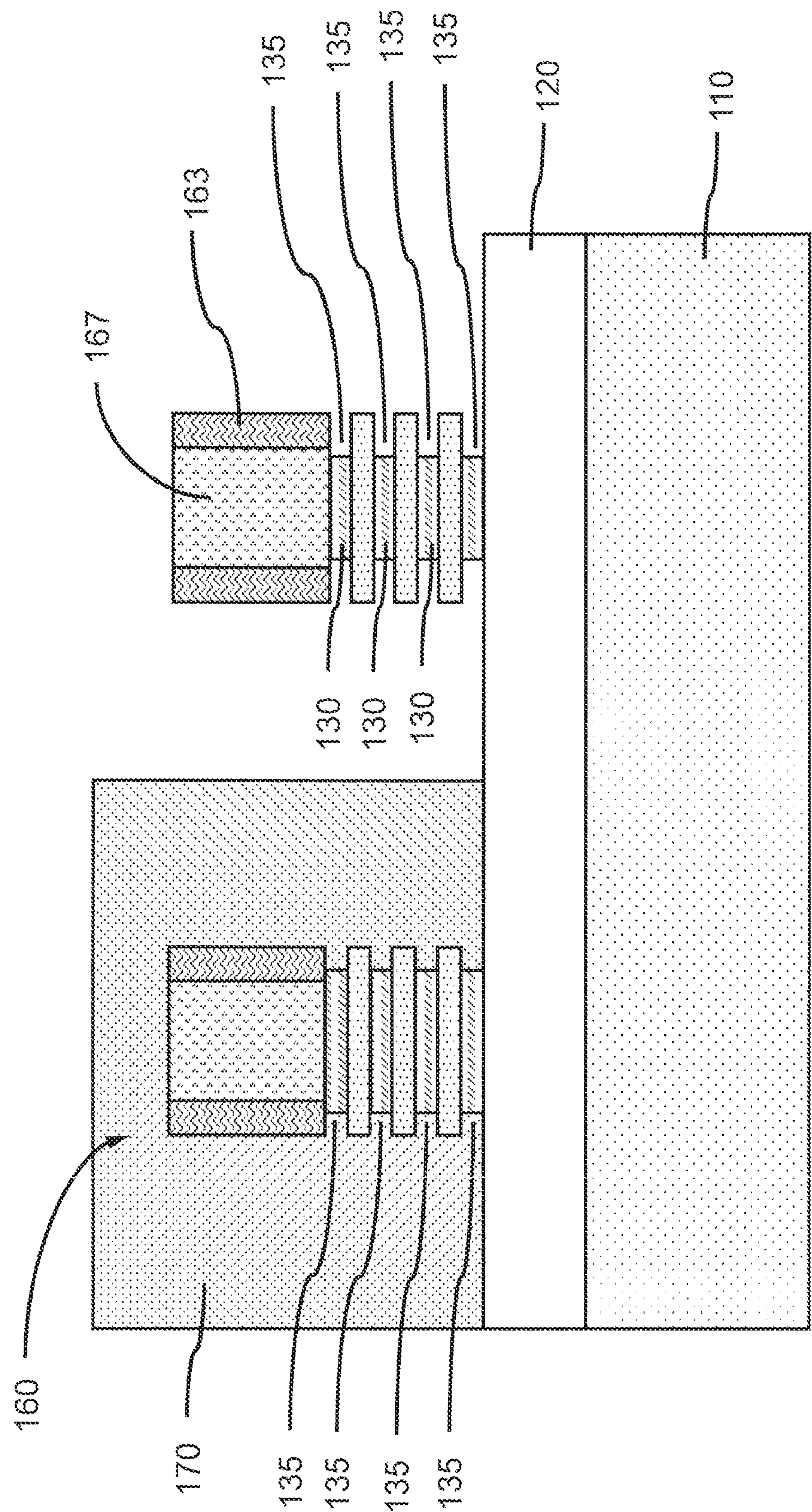


FIG. 7

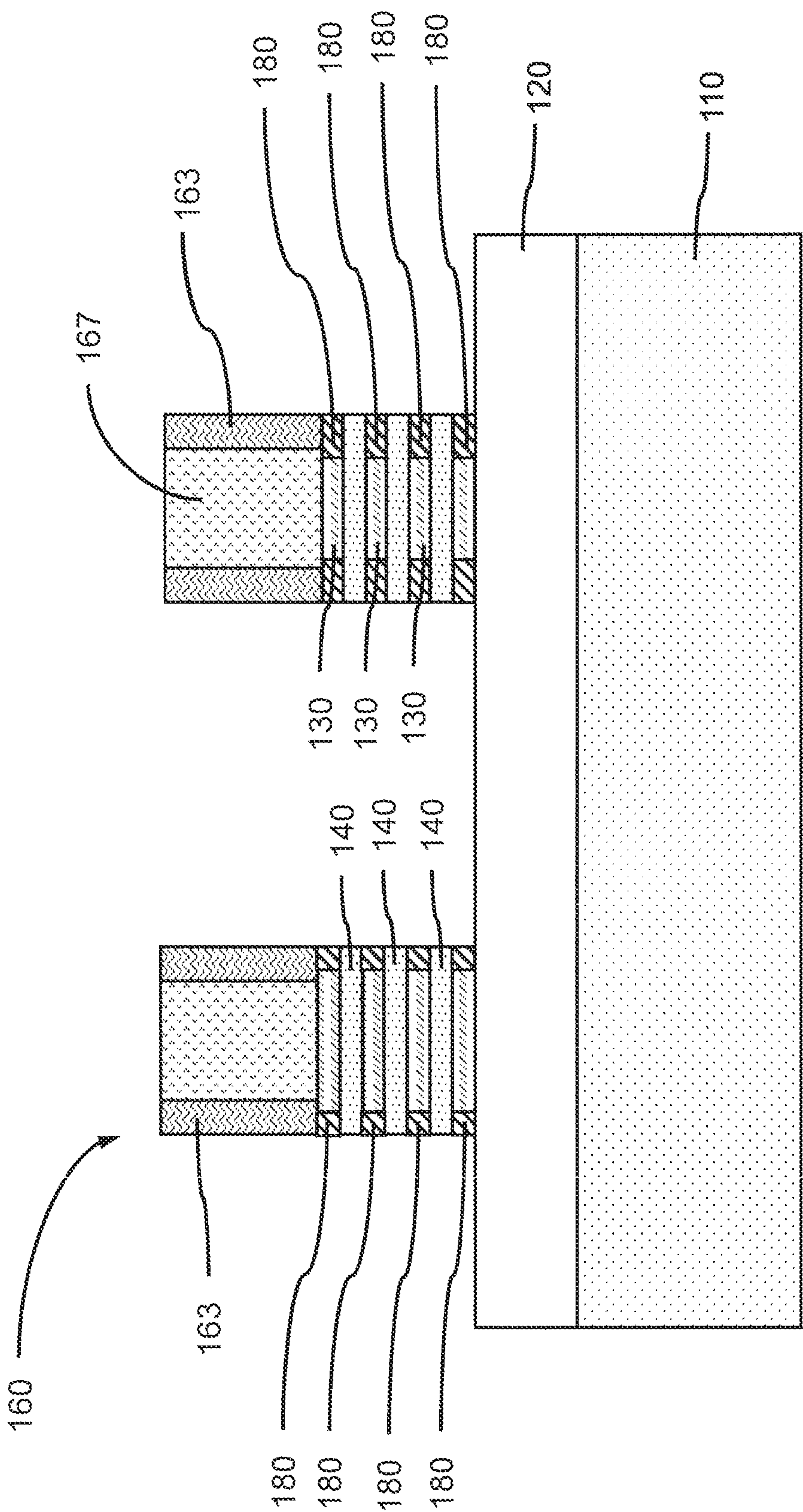


FIG. 8

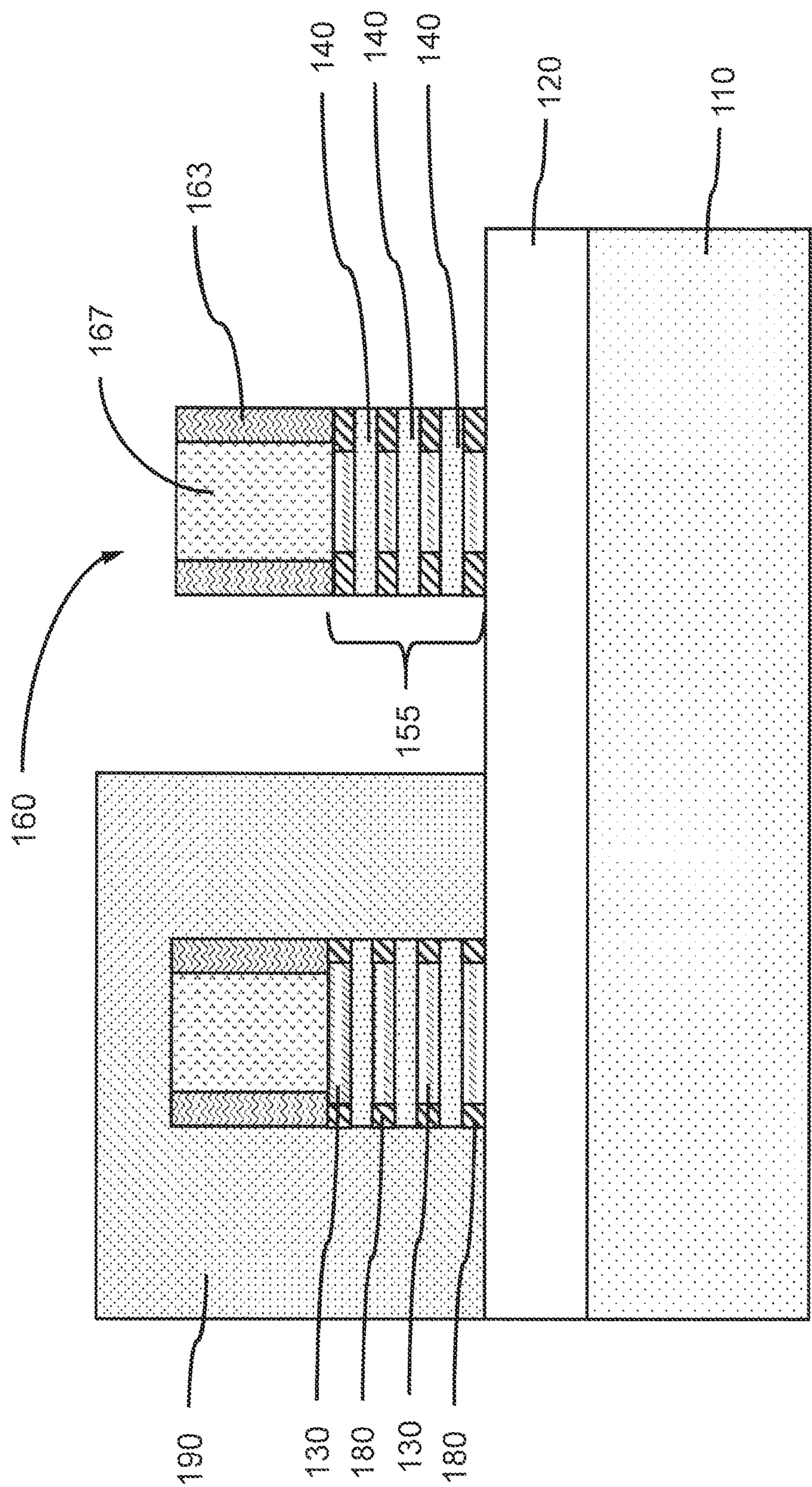


FIG. 9

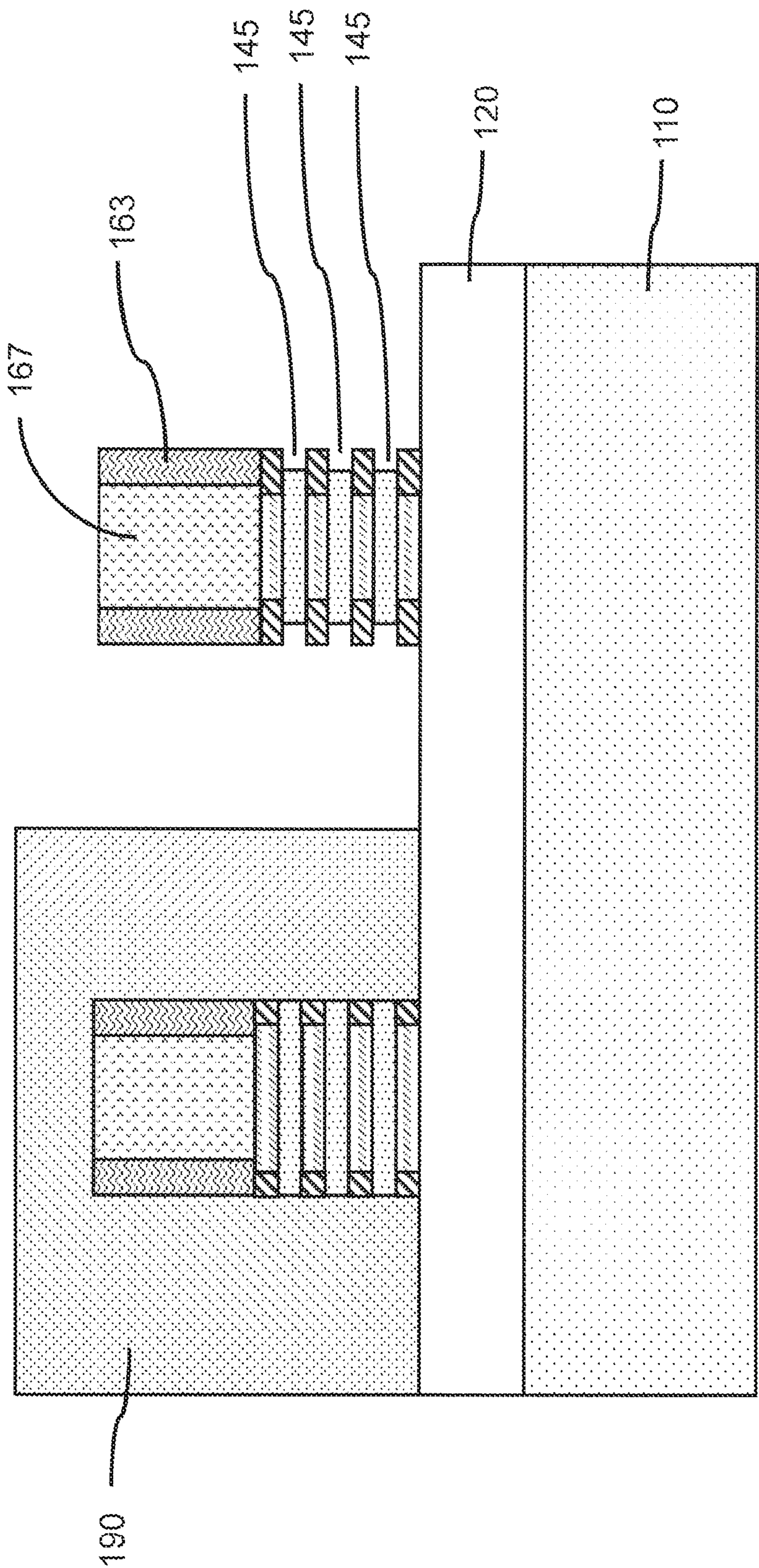


FIG. 10

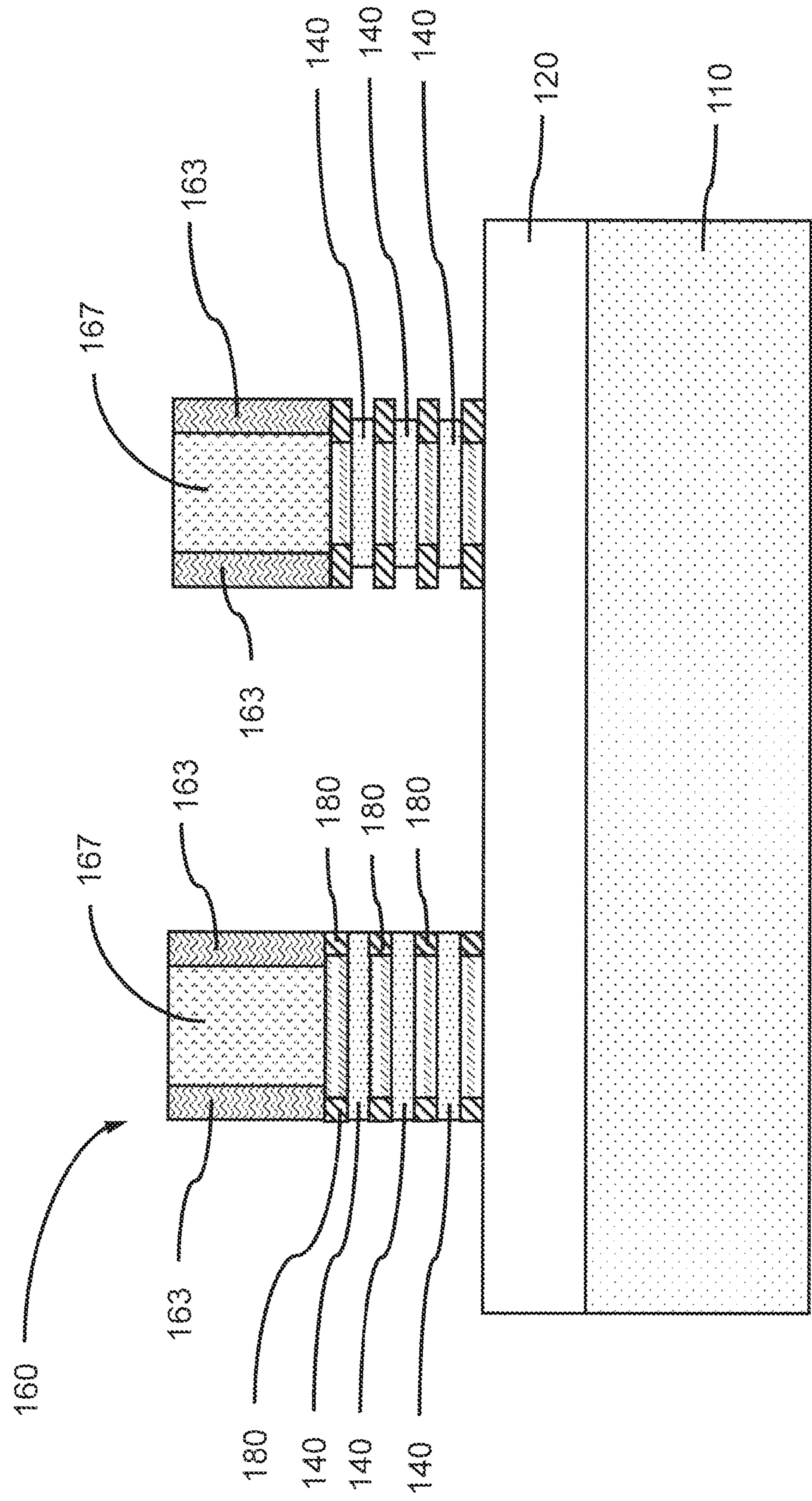
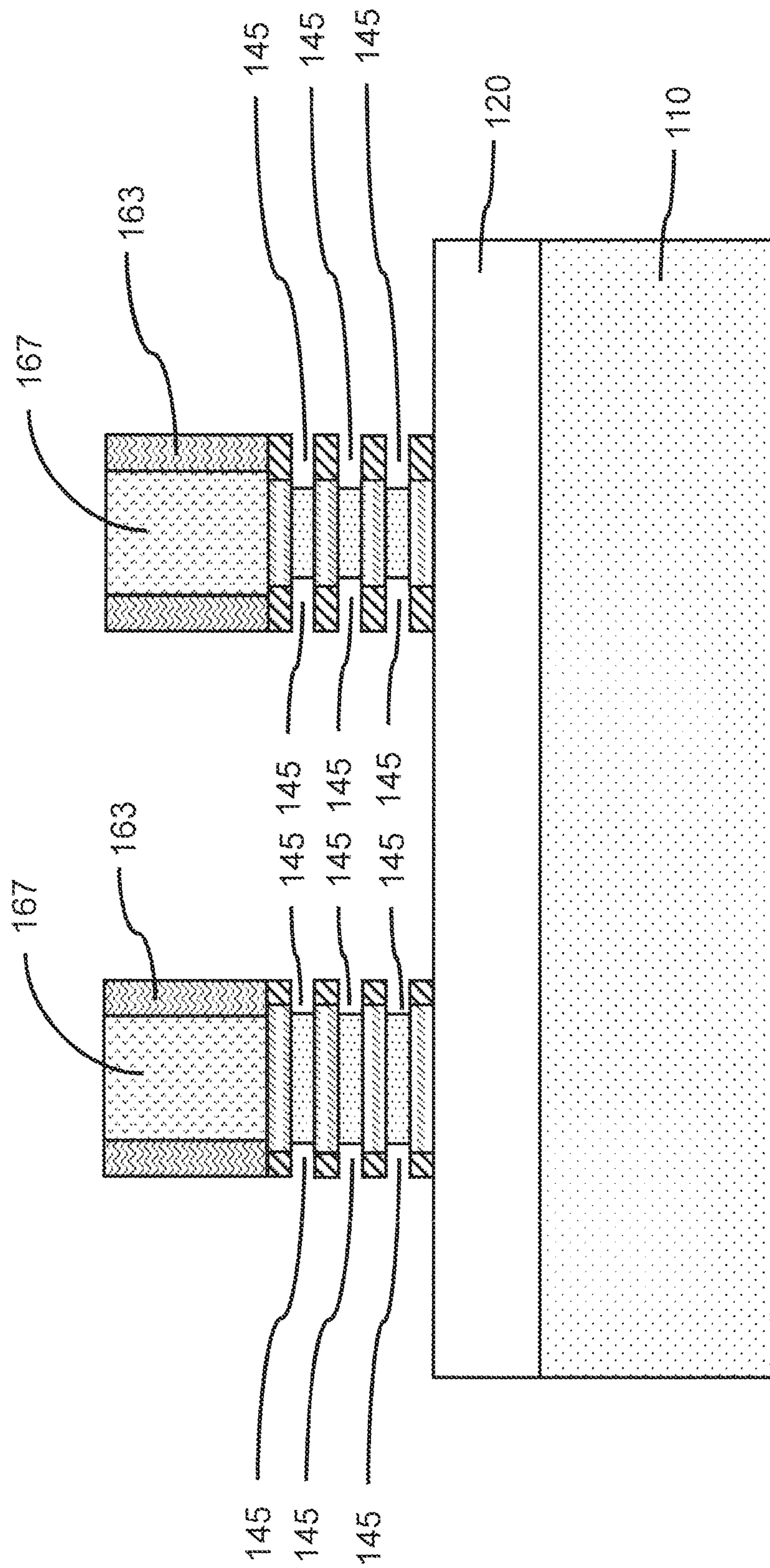


FIG. 11



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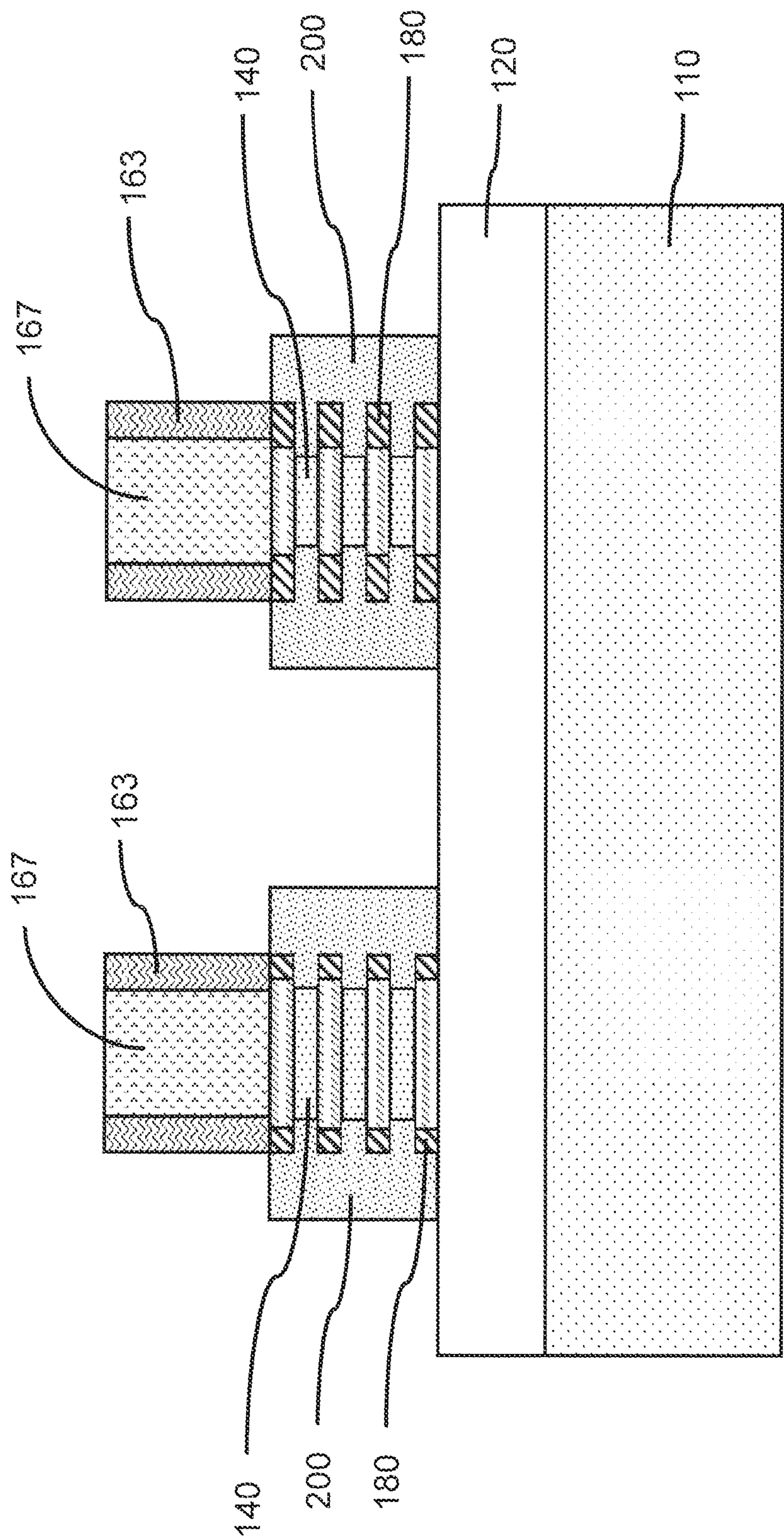


FIG. 13

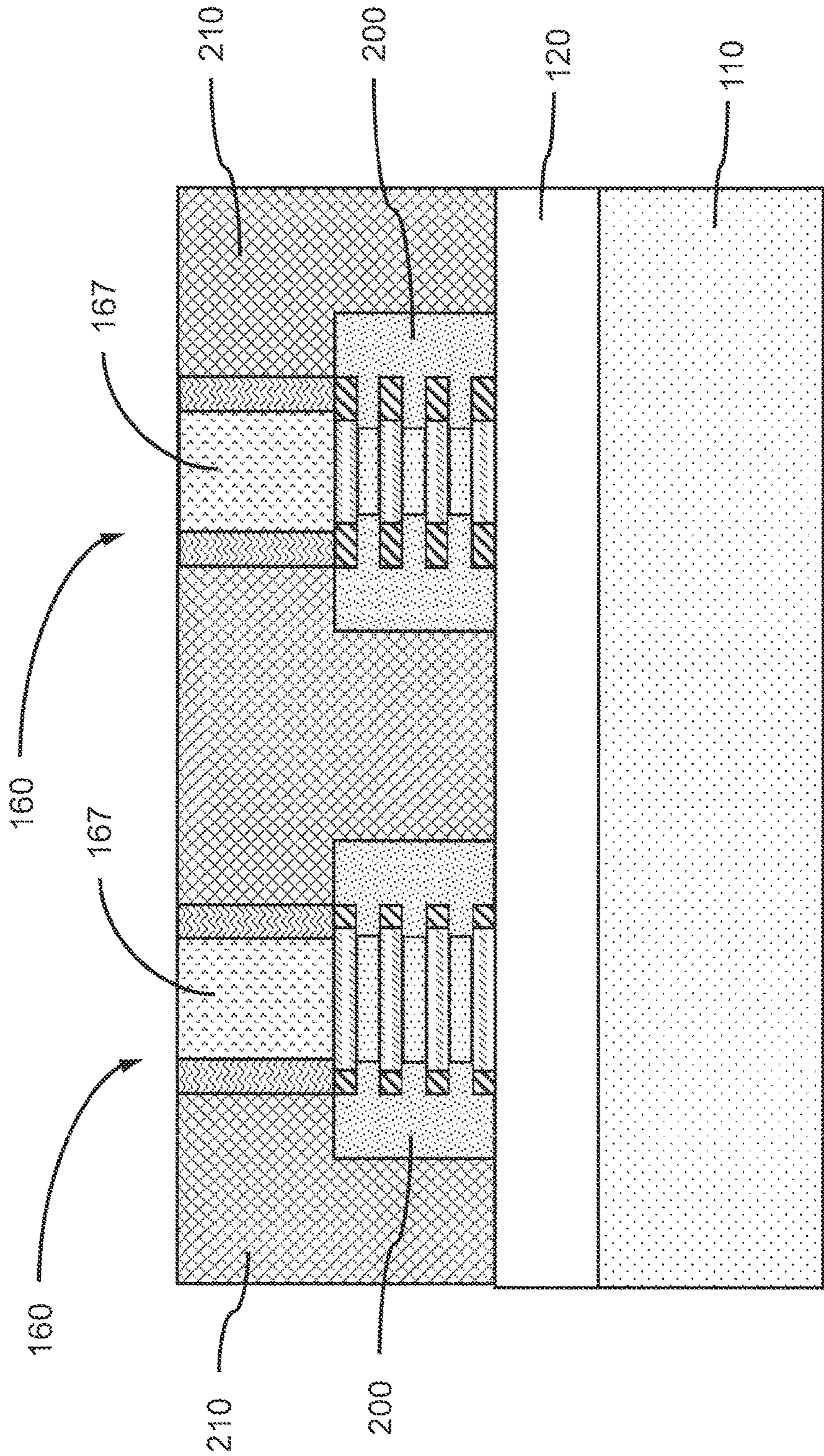


FIG. 14

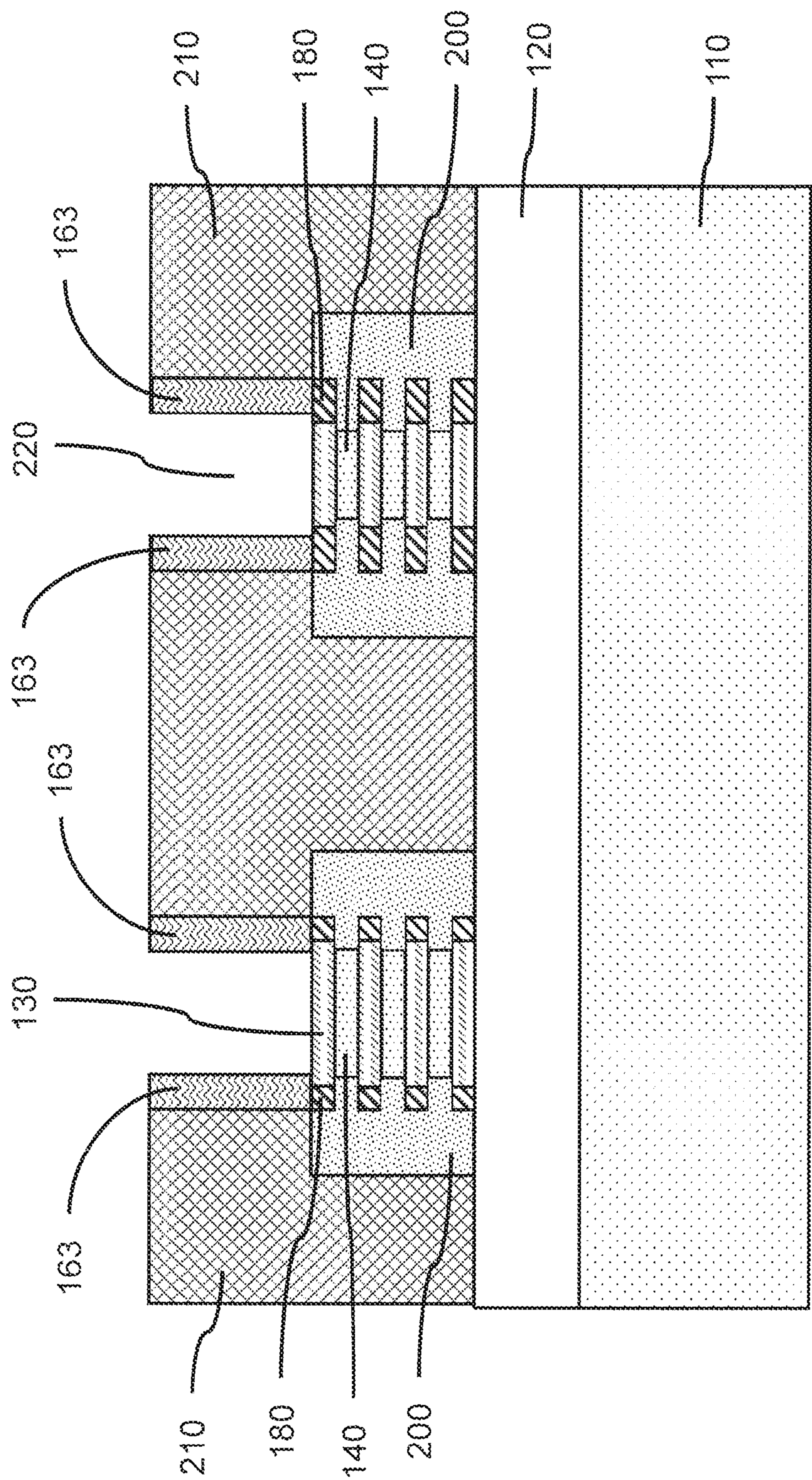
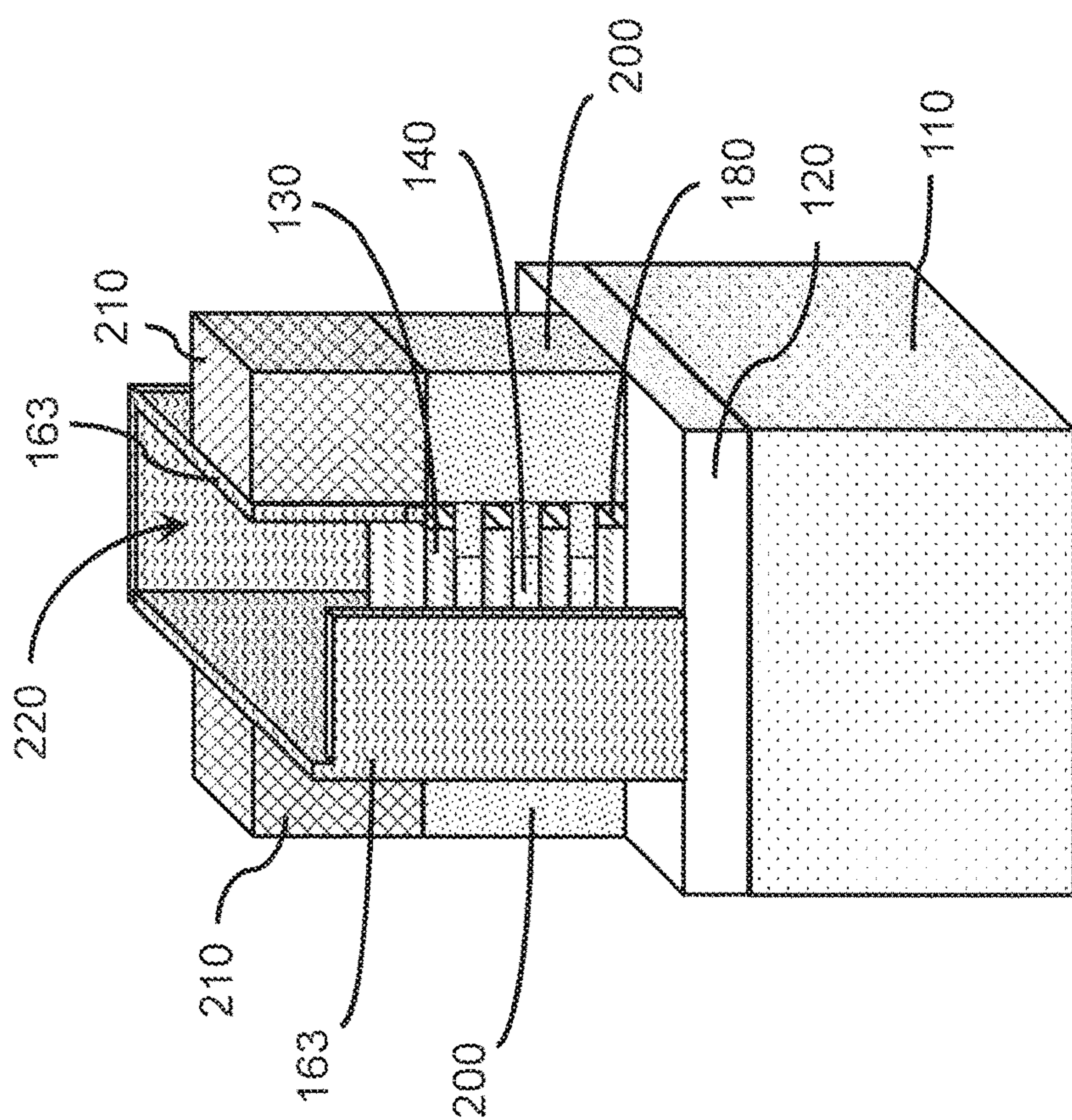
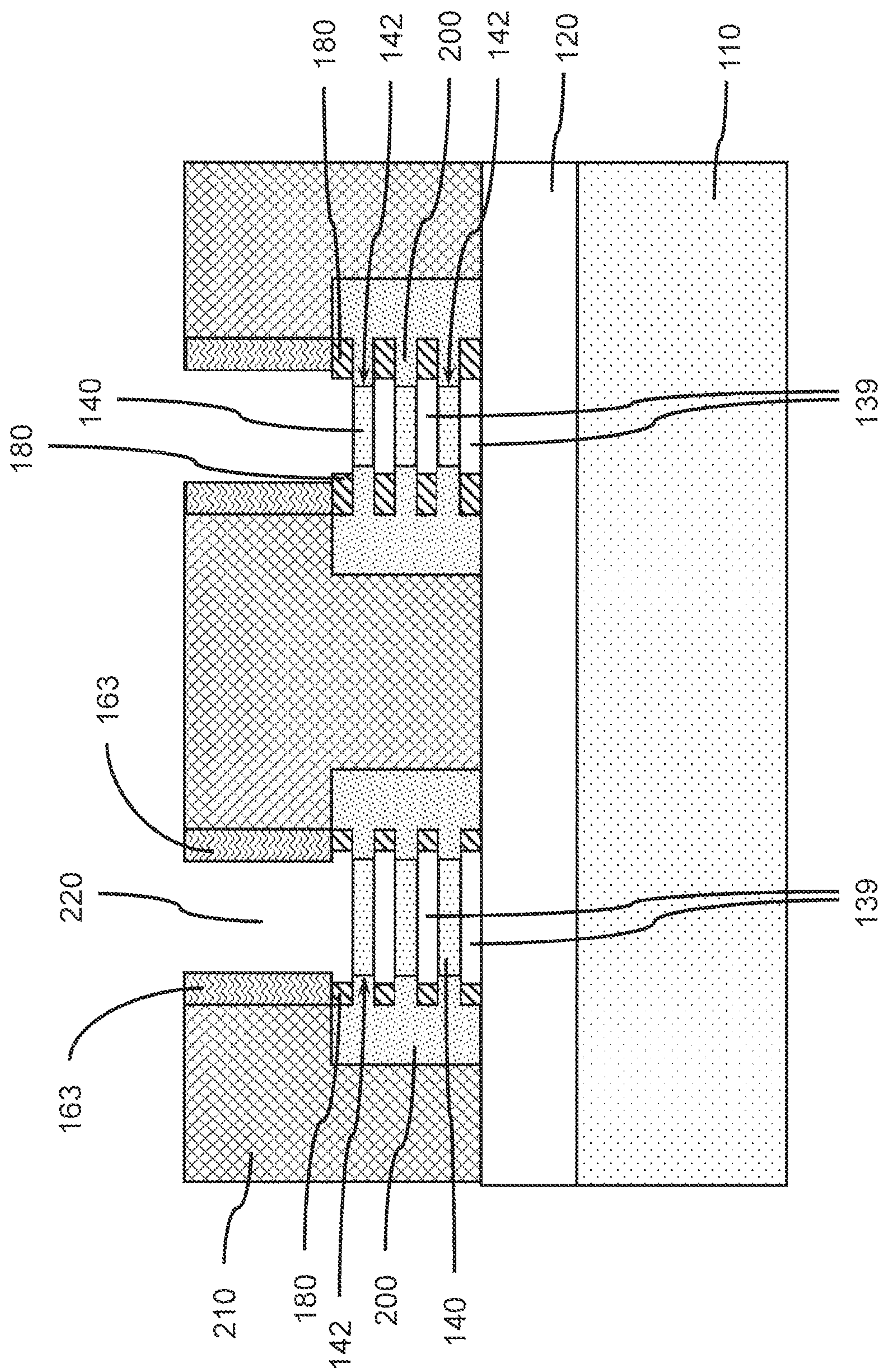


FIG. 15



GDM



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L

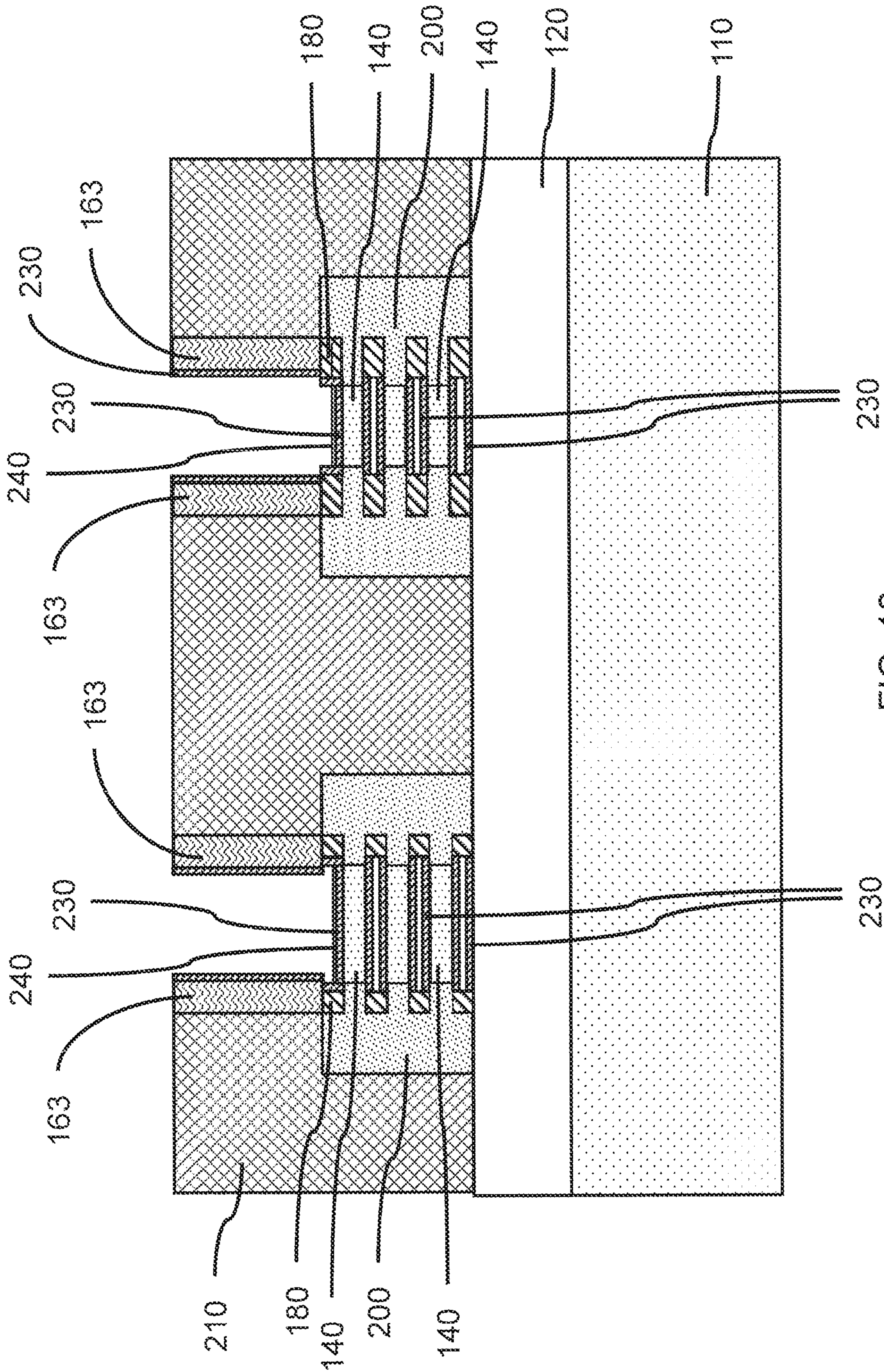


FIG. 18

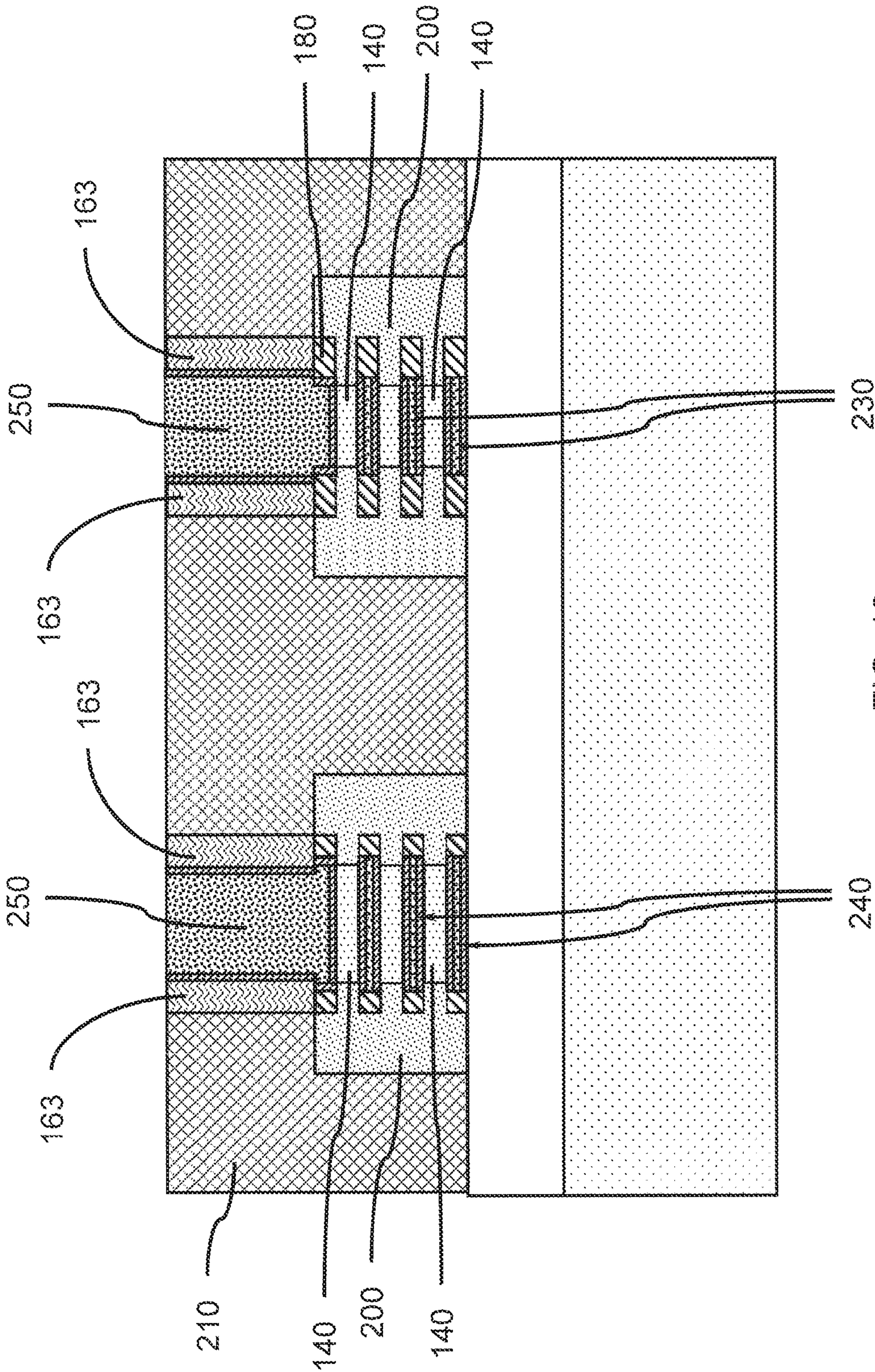


FIG. 19

FABRICATION OF NANO-SHEET TRANSISTORS WITH DIFFERENT THRESHOLD VOLTAGES

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; a claim printed with strikethrough indicates that the claim was canceled, disclaimed, or held invalid by a prior post-patent action or proceeding.

CROSS-REFERENCES TO RELATED APPLICATIONS

This application is a reissue application of U.S. Pat. No. 10,312,337, which issued based upon U.S. patent application Ser. No. 15/462,372, which is a continuation of U.S. application Ser. No. 15/268,993, filed Sep. 19, 2016, now U.S. Pat. No. 9,653,289. The aforementioned, earlier-filed applications are hereby incorporated by reference herein in their entirety.

BACKGROUND

Technical Field

The present invention generally relates to the fabrication of two or more nano-sheet transistors on the same substrate having different threshold voltages, and more particularly to forming different sized recesses to provide nano-sheet channels having different gate lengths.

Description of the Related Art

A Field Effect Transistor (FET) typically has a source, a channel, and a drain, where current flows from the source to the drain, and a gate that controls the flow of current through the channel. Field Effect Transistors (FETs) can have a variety of different structures, for example, FETs have been fabricated with the source, channel, and drain formed in the substrate material itself, where the current flows horizontally (i.e., in the plane of the substrate), and finFETs have been formed with the channel extending outward from the substrate, but where the current also flows horizontally from a source to a drain. The channel for the finFET can be an upright slab of thin rectangular Si, commonly referred to as the fin with a gate on the fin, as compared to a MOSFET with a single gate in the plane of the substrate. Depending on the doping of the source and drain, an n-FET or a p-FET can be formed.

Examples of FETs can include a metal-oxide-semiconductor field effect transistor (MOSFET) and an insulated-gate field-effect transistor (IGFET). Two FETs also can be coupled to form a complementary metal oxide semiconductor (CMOS), where a p-channel MOSFET and n-channel MOSFET are coupled together.

With ever decreasing device dimensions, forming the individual components and electrical contacts become more difficult. An approach is therefore needed that retains the positive aspects of traditional FET structures, while overcoming the scaling issues created by forming smaller device components.

SUMMARY

In accordance with an embodiment of the present invention, a method of forming two or more nano-sheet devices

with varying electrical gate lengths is provided. The method includes forming at least two cut-stacks including a plurality of sacrificial release layers and at least one alternating nano-sheet channel layer on a substrate. The method further includes removing a portion of the plurality of sacrificial release layers to form indentations having an indentation depth in the plurality of sacrificial release layers. The method further includes removing a portion of the at least one alternating nano-sheet channel layer to form a recess having a recess depth in the at least one alternating nano-sheet channel layers, where the recess depth is greater than the indentation depth.

In accordance with another embodiment of the present invention, a method of forming two or more nano-sheet devices with varying electrical gate lengths is provided. The method includes forming a channel stack including a plurality of sacrificial release layers and at least one alternating nano-sheet channel layer on a substrate. The method further includes forming two or more dummy gates including a dummy gate fill and a side spacer on the channel stack. The method further includes removing exposed portions of the channel stack not covered by the two or more dummy gates to form two or more cut-stacks. The method further includes removing a portion of the plurality of sacrificial release layers to form indentations having an indentation depth in the plurality of sacrificial release layers. The method further includes forming an indentation fill layer in the indentations. The method further includes forming a mask on at least one of the two or more cut-stacks. The method further includes removing a portion of the at least one alternating nano-sheet channel layer to form a recess in the unmasked cut-stacks.

In accordance with yet another embodiment of the present invention, a pair of adjacent nano-sheet devices on the same substrate is provided. The pair of adjacent nano-sheet devices includes a first nano-sheet device including, two source/drain regions on a substrate, where the two source/drain regions are separated by a distance, at least one nano-sheet channel layer having a length spanning the distance between the two source/drain regions, and a gate structure on the at least one nano-sheet channel layer having a physical gate length. The pair of adjacent nano-sheet devices includes a second nano-sheet device including, two source/drain regions on a substrate, where the two source/drain regions are separated by a distance, at least one nano-sheet channel layer having a length spanning the distance between the two source/drain regions, and a gate structure on the at least one nano-sheet channel layer having a physical gate length. The physical gate length of the first nano-sheet device is the same as the physical gate length of the second nano-sheet device, and the length of the at least one nano-sheet channel layer of the first nano-sheet device is different than the length of the at least one nano-sheet channel layer of the second nano-sheet device.

These and other features and advantages will become apparent from the following detailed description of illustrative embodiments thereof, which is to be read in connection with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The following description will provide details of preferred embodiments with reference to the following figures wherein:

FIG. 1 is a cross-sectional isometric view showing a plurality of nano-sheet layers separated by sacrificial release layers on an insulating layer of a substrate, in accordance with an embodiment of the present invention;

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FIG. 2 is a cross-sectional isometric view showing a plurality of patterned nano-sheet channel layers and sacrificial release layers on an insulating layer of a substrate, in accordance with an embodiment of the present invention;

FIG. 3 is a cross-sectional side view showing a patterned channel stack including nano-sheet channel layers and sacrificial release layers on an insulating layer of a substrate, in accordance with an embodiment of the present invention;

FIG. 4 is a cross-sectional side view showing two dummy gates with side spacers on a patterned channel stack of nano-sheet channel layers and sacrificial release layers, in accordance with an embodiment of the present invention;

FIG. 5 is a cross-sectional side view showing a dummy gate on each of two cut-stacks of nano-sheet channel layers and sacrificial release layers, in accordance with an embodiment of the present invention;

FIG. 6 is a cross-sectional side view showing indentations formed by removal of a portion of each sacrificial release layer in a cut-stack, in accordance with an embodiment of the present invention;

FIG. 7 is a cross-sectional side view showing enlarged indentations formed by removal of an additional portion of each sacrificial release layer of an unmasked cut-stack, in accordance with an embodiment of the present invention;

FIG. 8 is a cross-sectional side view showing indentation fill layers formed in the different sized indentations of each cut-stack, in accordance with an embodiment of the present invention;

FIG. 9 is a cross-sectional side view showing a masked cut stack and an unmasked cut-stack, in accordance with an embodiment of the present invention;

FIG. 10 is a cross-sectional side view showing recesses formed by removal of a portion of each nano-sheet channel layer of an unmasked cut-stack, in accordance with an embodiment of the present invention;

FIG. 11 is a cross-sectional side view of an unmasked cut-stack with recessed nano-sheet channel layers and an unmasked cut-stack without recessed nano-sheet channel layers, in accordance with an embodiment of the present invention;

FIG. 12 is a cross-sectional side view of two cut-stacks having different sized recesses formed in the nano-sheet channel layers, in accordance with an embodiment of the present invention;

FIG. 13 is a cross-sectional side view of source/drain regions formed on the nano-sheet channel layers on either side of each of the two cut-stacks, in accordance with an embodiment of the present invention;

FIG. 14 is a cross-sectional side view of an interlayer dielectric (ILD) formed on the two cut-stacks and dummy gates, in accordance with an embodiment of the present invention;

FIG. 15 is a cross-sectional side view of an interlayer dielectric on the two cut-stacks after removal of the dummy gate fill, in accordance with an embodiment of the present invention;

FIG. 16 is a cut-away isometric view of the long axis of the patterned nano-sheet device after removing the dummy gate fill from within the side spacer, in accordance with an embodiment of the present invention;

FIG. 17 is a cross-sectional side view of a plurality of freed nano-sheet channel layers after removal of the intervening sacrificial release layers in the two cut-stacks, in accordance with an embodiment of the present invention;

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FIG. 18 is a cross-sectional side view of a gate dielectric layer on the exposed surfaces of the nano-sheets and side spacers, in accordance with an embodiment of the present invention; and

FIG. 19 is a cross-sectional side view of a gate structure on the nano-sheets of each of the cut-stacks, in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION

Principles and embodiments of the present invention relate to fabricating a plurality of transistor devices utilizing nano-sheets for the channel of the devices, where the nano-sheets have different lengths. The electrical gate length, L_{Ge} , of the different devices can be varied by using a sequence of etching steps to modify the nano-sheet lengths. The different gate lengths can provide different threshold voltages, V_T .

Principles and embodiments of the present invention also relate to forming nano-sheet transistor devices having different threshold voltages adjacent to each other on the same substrate by controlling the number of etching steps each transistor device undergoes during fabrication. Multiple timed etches can be used to remove predetermined amounts of each exposed nano-sheet channel layer to produce a cut-stack with a predetermined electrical gate length and threshold voltage, while neighboring nano-sheet transistor devices are masked during the etching steps.

Principles and embodiments of the present invention also relate to forming a plurality of nano-sheet devices having nano-sheets initially with the same dimensions, and selectively removing predetermined portions of the nano-sheets to produce nano-sheet devices having different nano-sheet channel layers with different final dimensions.

Principles and embodiments of the present invention relate to controlling threshold voltages of nano-sheet devices without using channel doping.

Exemplary applications/uses to which the present invention can be applied include, but are not limited to: transistors for complementary metal-oxide-semiconductor (CMOS) devices, logic devices (e.g., NAND gates, NOR gates, XOR gates, etc.), memory devices (e.g., DRAM, SRAM, flip-flops, etc.), etc.

In various embodiments, the materials and layers can be deposited by physical vapor deposition (PVD), chemical vapor deposition (CVD), atomic layer deposition (ALD), molecular beam epitaxy (MBE), or any of the various modifications thereof, for example, plasma-enhanced chemical vapor deposition (PECVD), metal-organic chemical vapor deposition (MOCVD), low pressure chemical vapor deposition (LPCVD), electron-beam physical vapor deposition (EB-PVD), and plasma-enhanced atomic layer deposition (PEALD). The depositions can be epitaxial processes, and the deposited material can be crystalline. In various embodiments, formation of a layer may be by one or more deposition processes, where, for example, a conformal layer can be formed by a first process (e.g., ALD, PEALD, etc.) and a fill can be formed by a second process (e.g., CVD, electrodeposition, PVD, etc.).

It is to be understood that the present invention will be described in terms of a given illustrative architecture; however, other architectures, structures, substrate materials and process features and steps may be varied within the scope of the present invention.

It should be noted that certain features may not be shown in all figures for the sake of clarity. This is not intended to be interpreted as a limitation of any particular embodiment, or illustration, or scope of the claims.

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Reference to source/drain projections, layers, regions, etc., is intended to indicate that the particular device feature can be implemented as a source or a drain except as expressly indicated otherwise. In addition, the role of source and drain for an active device can in some instances be reversed, so a previously indicated drain may instead be a source and vice versa. Reference to a source/drain is, therefore, intended to encompass the broadest reasonable scope of the term.

Referring now to the drawings in which like numerals represent the same or similar elements and initially to FIG. 1, a cross-sectional isometric view of a plurality of nano-sheet layers separated by sacrificial release layers on an insulating layer of a substrate is shown, in accordance with an embodiment of the present invention.

In one or more embodiments, a substrate **110** can be a semiconductor or an insulator with an active surface semiconductor layer (ASL). The substrate can be crystalline, semi-crystalline, microcrystalline, or amorphous. The substrate can be essentially (i.e., except for contaminants) a single element (e.g., silicon), primarily (i.e., with doping) of a single element, for example, silicon (Si) or germanium (Ge), or the substrate can include a compound, for example, Al_2O_3 , SiO_2 , GaAs, SiC, or SiGe.

In one or more embodiments, the substrate can have multiple material layers, for example, a semiconductor-on-insulator substrate (SeOI), a silicon-on-insulator substrate (SOI), germanium-on-insulator substrate (GeOI), or silicon-germanium-on-insulator substrate (SGOI), where an active surface semiconductor layer of the substrate **110** can be on a substrate insulator layer **120** (e.g., buried oxide layer (BOX)). The substrate **110** can also have other layers forming the substrate, including high-k oxides and/or nitrides.

In one or more embodiments, a substrate insulator layer **120** (e.g., BOX layer) can be formed on at least a portion of a substrate **110**. An active surface semiconductor layer can be on the BOX layer. The active surface semiconductor layer can be on the buried oxide (BOX) layer, which physically separates and electrically insulates the active surface layer from a mechanically supporting portion of the substrate **110**.

In various embodiments, the substrate may be a single crystal silicon (Si), silicon germanium (SiGe), or III-V semiconductor (e.g., GaAs) wafer, or have a single crystal silicon (Si), silicon germanium (SiGe), or III-V semiconductor (e.g., GaAs) active surface layer. In one or more embodiments, the substrate **110** can be a silicon wafer.

In one or more embodiments, a plurality of sacrificial release layers **130** can be formed with one or more alternating nano-sheet channel layers **140** on a substrate **110**, where the substrate **110** can be a semiconductor-on-insulator (SeOI) substrate with either a sacrificial release layer **130** or a nano-sheet channel layer **140** forming the active surface semiconductor layer directly on the substrate insulator layer **120**. The plurality of sacrificial release layers **130** and at least one alternating nano-sheet channel layer(s) **140** can form a stack on the substrate **110**. In various embodiments, there can be N sacrificial release layers **130** and N-1 nano-sheet channel layers **140**, where a sacrificial release layer can be between the substrate **110** and a nano-sheet channel layer **140**, and a sacrificial release layer can be the upper-most layer in the stack. For example, there can be two sacrificial release layers **130** and one nano-sheet channel layer **140** between and separating the two sacrificial release layers **130**.

In various embodiments, the top-most sacrificial release layer **130** may be optional, such that there are N sacrificial

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release layers **130** and N nano-sheet channel layers **140**, where a sacrificial release layer **130** can be between the substrate insulator layer **120** and a nano-sheet channel layer **140**. Removal of a dummy gate fill could thereby expose the top-most nano-sheet channel layer **140**.

In a non-limiting exemplary embodiment, the substrate **110** can be a silicon-germanium-on-insulator substrate having a silicon-germanium active surface layer as the bottom-most sacrificial release layer **130** on the substrate insulator layer **120**. In various embodiments, a single crystal, active surface layer (e.g., silicon, silicon-germanium, etc.) may be formed on the substrate insulator layer **120** by a layer transfer method, as would be known in the art.

In various embodiments, the sacrificial release layers **130** can have a top surface, a bottom surface, and a thickness there between, where the sacrificial release layers **130** can be formed on the surface of the substrate **110** or substrate insulator layer **120**. In various embodiments, the sacrificial release layer **130** or nano-sheet channel layer **140** can be epitaxially grown on a crystalline surface of the substrate **110**. The sacrificial release layers **130** can be heteroepitaxially deposited on an exposed crystalline surface, for example, on a crystalline nano-sheet channel layer **140**. The sacrificial release layers **130** can be a different material than the substrate material, substrate insulator layer **120**, and/or the material of the nano-sheet channel layer **140**, such that the sacrificial release layers **130** can be selectively removed, for example, by an etching process.

In one or more embodiments, the sacrificial release layers **130** can have a thickness in the range of about 5 nm to about 20 nm, or in the range of about 10 nm to about 15 nm, or about 10 nm, although other thicknesses are also contemplated.

In one or more embodiments, a sacrificial release layer **130** can be made of a material that can be selectively etched compared to the material of the nano sheet channel layer **140** and/or substrate **110** material, such that the sacrificial release layers **130** can be selectively removed from between nano-sheet channel layers **140**. In a non-limiting exemplary embodiment, the sacrificial release layer **130** can be silicon-germanium ($\text{Si}_x\text{Ge}_{1-x}$), where the germanium concentration can be about 20 at. % to about 70 at. %, or about 30 at. % to about 50 at. %, or about 30 at. % (atomic percent).

In one or more embodiments, the nano-sheet channel layer **140** can be epitaxially formed on an underlying crystalline sacrificial release layer **130**. In a non-limiting exemplary embodiment, the sacrificial release layers **130** can be crystalline SiGe layers having predetermined crystal orientation for growing nano-sheet channel layers **140**. In a non-limiting exemplary embodiment, the nano-sheet channel layer(s) **140** can be a single crystal silicon layer on the crystalline sacrificial release layer **130**. In another non-limiting exemplary embodiment, the sacrificial release layers **130** can be crystalline silicon layers and the nano-sheet channel layer(s) **140** can be a single crystal silicon-germanium layer(s), where the sacrificial release layers **130** can be selectively etched relative to the nano-sheet channel layer(s) **140**.

FIG. 2 is a cross-sectional isometric view showing a plurality of patterned nano-sheet channel layers and sacrificial release layers on an insulating layer of a substrate, in accordance with an embodiment of the present invention.

In one or more embodiments, the stack of alternating sacrificial release layers **130** and nano-sheet channel layers **140** can be masked and patterned, as would be known in the art to form a channel stack **150** having a long lateral dimension (i.e., length), a short lateral dimension (i.e.,

width), and a height. A portion of the stack of sacrificial release layers **130** and nano-sheet channel layers **140** can be removed, for example, by a directional etch (e.g., reactive ion etch (RIE)) to form a channel stack **150**. The directional etch may be a non-selective, timed RIE to remove unmasked portions of the sacrificial release layers **130** and nano-sheet channel layers **140** through a single etching step, or alternating selective RIEs may be used to remove exposed portion(s) of each layer separately.

FIG. **3** is a cross-sectional side view showing a patterned channel stack including nano-sheet channel layers and sacrificial release layers on an insulating layer of a substrate, in accordance with an embodiment of the present invention.

In one or more embodiments, the patterned channel stack **150** may be sufficiently long to form a plurality of dummy gates on the channel stack, where portions of the channel stack between dummy gates may be removed to form separate nano-sheet devices. Two or more dummy gates can be formed on the same channel stack **150**.

FIG. **4** is a cross-sectional side view showing two dummy gates with side spacers on a patterned channel stack of nano-sheet channel layers and sacrificial release layers, in accordance with an embodiment of the present invention.

In one or more embodiments, one or more dummy gates **160** can be formed on the channel stack **150**. A dummy gate can include side spacers **163** and a dummy gate fill **167**. The dummy gate(s) **160** can be formed by processes known in the art, including masking, patterning, etching, deposition, and planarization processes/steps. In various embodiments, the dummy gate(s) **160** can be formed by a double patterning process (e.g., sidewall image transfer (SIT)). The side spacer **163** can be completely around the dummy gate fill **167**.

In one or more embodiments, a dummy gate **160** can be formed on a channel stack **150**, where the dummy gate **160** can be formed over three sides of the channel stack. In various embodiments, the dummy gate **160** can be a material that can be easily and selectively removed from the layers of the channel stack **150**, including, but not limited to, polysilicon (p-Si), amorphous silicon (a-Si), amorphous carbon (a-C), silicon oxide (SiO), silicon nitride (SiN), silicon oxynitride (SiON), and combinations thereof. In various embodiments, the dummy gate **160** may include multiple material layers (e.g., a capping layer), where the dummy gate can be a dummy gate stack.

In one or more embodiments, a side spacer **163** can be formed on each of the dummy gate fills **167**. The side spacer **163** can be conformally deposited on the dummy gate fill **167** and exposed surfaces of the channel stack **150**, and etched back using a directional etch (e.g. RIE) to expose the top surface of the dummy gate fill **167**, the channel stack **150**, and the substrate surface, while remaining on the vertical surfaces of the dummy gate fills **167**.

In various embodiments, the side spacer **163** can be a silicon nitride (SiN), a silicon oxynitride (SiON), a silicon carbonitride (SiCN), a silicon boronitride (SiBN), a silicon borocarbide (SiBC), a silicon boro carbonitride (SiBCN), a boron carbide (BC), a boron nitride (BN), or combinations thereof, where the dummy gate fill **167** can be selectively etched relative to the side spacer **163**.

FIG. **5** is a cross-sectional side view showing a dummy gate on each of two cut-stacks of nano-sheet channel layers and sacrificial release layers, in accordance with an embodiment of the present invention.

In one or more embodiments, the portions of the channel stack **150** exposed between the dummy gates **160** can be removed to form cut-stacks **155**, where the dummy gates can mask the cut-stacks, and the cut-stacks can have the same

resulting lateral dimension as the dummy gate **160**. The exposed portions of the channel stacks can be removed using a directional etch (e.g., RIE) to form essentially vertical sides to the cut-stack **155**. The cut-stack **155** includes the alternating sacrificial release layers **130** and nano-sheet channel layer(s) **140**, where the ends of the sacrificial release layers **130** and nano-sheet channel layer(s) **140** are exposed.

FIG. **6** is a cross-sectional side view showing indentations formed by removal of a portion of each sacrificial release layer in a cut-stack, in accordance with an embodiment of the present invention.

In one or more embodiments, a portion of the sacrificial release layers **130** can be removed to reduce the size of the sacrificial release layers in at least one lateral dimension (i.e., length, width). The portion of the sacrificial release layers **130** can be removed using an isotropic etch (e.g., wet chemical etch, non-directional dry plasma etch, etc.), where the isotropic etch etches laterally into the sacrificial release layers **130**. The isotropic etch can remove a predetermined amount of material from the sacrificial release layers **130**, where the etch can be a timed etch to uniformly remove an equal amount of material from each exposed end. The isotropic etch can form indentations **135** having a predetermined indentation depth into the sacrificial release layers **130**. After a first etching process, the nano-sheet channel layers **140** can extend past the sacrificial release layers **130** by a predetermined distance. Each of the indentations **135** can extend into the area below the side spacer **163** and dummy gate **167**.

In one or more embodiments, the indentations **135** can have an indentation depth in the range of about 2 nm to about 10 nm, or in the range of about 2 nm to about 5 nm, or in the range of about 5 nm to about 10 nm, although other depths are also contemplated. The depth of the indentation can determine the remaining length of the sacrificial release layers **130** below the dummy gate(s) **160**, and thereby the width of a subsequently formed gate fill layer and/or gate electrode at the bottom of the gate structure. The depth of the indentation can also determine, at least in part, the amount of capacitive overlap, C_{ov} , between the gate structure and the nano-sheet channel layer(s) **140**.

FIG. **7** is a cross-sectional side view showing enlarged indentations formed by removal of an additional portion of each sacrificial release layer of an unmasked cut-stack, in accordance with an embodiment of the present invention.

In one or more embodiments, a mask **170** can be formed on the one or more dummy gates **160** and cut-stacks **155**, for example, with an organic resist material or spin-on layer, leaving one or more dummy gates **160** and cut-stacks **155** exposed for etching, as would be known in the art.

In one or more embodiments, additional portions of the one or more exposed sacrificial release layers **130** can be removed using a second timed isotropic etch, for example, a wet etch or isotropic dry plasma etch, where the etchant can enter into the indentations **135** formed by the first etch. In various embodiments, the indentations **135** can extend below the dummy gate fill **167** and side spacer **163**, where the isotropic etch selectively removes sacrificial release layer material not otherwise exposed. Additional etching steps may be used to remove additional material from one or more cut-stacks **155**. The indentation depth of the previously formed indentations **135** can thereby be increased.

The sacrificial release layers **130** of the masked cut-stack **155** can remain unaffected by the second and any subsequent etching steps, so the initially formed indentations **135** can remain the same depth. In various embodiments, the mask **170** can be removed from one or more of the masked

cut-stacks **155** subsequent to the second etch, and a third timed etch may be used to remove additional material from both the previously masked cut-stack and the exposed cut-stack to achieve three different predetermined etch depths for the indentations **135**. The process can be repeated to prepare multiple cut-stacks **155** with different indentation depths on the substrate **110**. The indentation depth of the previously formed indentations **135** can thereby be increased, while indentations of a different depth can thereby be created in the sacrificial release layers **130** of a different cut-stack **155**.

FIG. **8** is a cross-sectional side view showing indentation fill layers formed in the different sized indentations of each cut-stack, in accordance with an embodiment of the present invention.

In one or more embodiments, an indentation fill layer **180** can be formed on the one or more nano-sheet channel layer(s) **140** and one or more sacrificial release layers **130**, where the indentation fill layer **180** can fill the indentations **135** adjacent to the remaining portion of the sacrificial release layers **130**, and between overhanging nano-sheet channel layer(s) **140**. The indentation fill layer **180** can be formed on at least a portion of the substrate **110** and dummy gate **160**, and may be etched back by the RIE to leave the indentation fill layers **180** in the indentations **135**.

In one or more embodiments, the indentation fill layer **180** can be formed by ALD, PEALD, CVD, PECVD, or combinations thereof, where the indentation fill layer **180** can be conformally deposited within the indentations **135** (e.g., by ALD) to fill the indentations. Portions of the indentation fill layer **180** that extend out beyond the side spacers **163** of the dummy gate can be removed by a directional etch (e.g., RIE).

In one or more embodiments, the indentation fill layer **180** can be a silicon nitride (SiN), a silicon oxide (SiO), silicon oxynitride (SiON), silicon oxycarbide (SiOC), a silicon boron carbonitride (SiBCN), a silicon oxy carbonitride (SiOCN), a silicon carbide (SiC), a high-k metal oxide, a low-k insulator, or suitable combinations thereof.

In various embodiments, the low-k insulator can include, but is not limited to, a fluoride-doped silicon oxide (e.g., fluoride doped glass), a carbon-doped silicon oxide, a porous silicon oxide, a spin-on silicon based polymeric material (e.g., tetraethyl orthosilicate/hydrogen (TEOS), silsesquioxane (HSQ) and methylsilsesquioxane (MSQ)), or combinations thereof. A low-k insulator material can have a dielectric constant of less than 3.9.

In various embodiments, the high-K metal oxide can include, but is not limited to, transition metal oxides such as hafnium oxide (e.g., HfO_2), hafnium silicon oxide (e.g., HfSiO_4), hafnium silicon oxynitride ($\text{Hf}_w\text{Si}_x\text{O}_y\text{N}_z$), lanthanum oxide (e.g., La_2O_3), lanthanum aluminum oxide (e.g., LaAlO_3), zirconium oxide (e.g., ZrO_2), zirconium silicon oxide (e.g., ZrSiO_4), zirconium silicon oxynitride ($\text{Zr}_w\text{Si}_x\text{O}_y\text{N}_z$), tantalum oxide (e.g., TaO_2 , Ta_2O_5), titanium oxide (e.g., TiO_2), barium strontium titanium oxide (e.g., BaTiO_3 — SrTiO_3), barium titanium oxide (e.g., BaTiO_3), strontium titanium oxide (e.g., SrTiO_3), yttrium oxide (e.g., Y_2O_3), aluminum oxide (e.g., Al_2O_3), lead scandium tantalum oxide ($\text{Pb}(\text{Sc}_x\text{Ta}_{1-x})\text{O}_3$), and lead zinc niobate (e.g., $\text{PbZn}_{1/3}\text{Nb}_{2/3}\text{O}_3$). The high-k material can further include dopants such as lanthanum and/or aluminum. The stoichiometry of the high-K compounds can vary.

FIG. **9** is a cross-sectional side view showing a masked cut stack and an unmasked cut-stack, in accordance with an embodiment of the present invention.

In one or more embodiments, one or more dummy gates **160** and cut-stacks **155** on the substrate **110** can be covered by a second masking layer **190**, where the second masking layer **190** can be an organic resist or organic planarization material (e.g., poly methyl methacrylate (PMMA)). One or more cut-stacks can remain exposed.

FIG. **10** is a cross-sectional side view showing recesses formed by removal of a portion of each nano-sheet channel layer of an unmasked cut-stack, in accordance with an embodiment of the present invention.

In one or more embodiments, a portion of the nano-sheet channel layers **140** can be removed to reduce the size of the nano-sheet channel layers in at least one lateral dimension (i.e., length, width). The portion of the nano-sheet channel layers **140** can be removed using a selective isotropic etch (e.g., wet chemical etch, non-directional dry plasma etch, etc.), where the isotropic etch etches laterally into the nano-sheet channel layers **140** of the unmasked cut-stack **155**. The isotropic etch can remove a predetermined amount of material from the nano-sheet channel layers **140**, where the etch can be a timed etch to uniformly remove an equal amount of material from the exposed ends of the nano-sheet channel layers **140**. The isotropic etch can form recesses **145** having a predetermined recess depth into the nano-sheet channel layers **140**. After a first etching process, the indentation fill layers **180** can extend past the ends of the nano-sheet channel layers **140** by a predetermined distance. Each of the recesses **145** can extend into the area below the side spacer **163** and dummy gate **167**. In various embodiments, the mask **190** can be removed from one or more of the masked cut-stacks **155** subsequent to the first etch.

FIG. **11** is a cross-sectional side view of an unmasked cut-stack with recessed nano-sheet channel layers and an unmasked cut-stack without recessed nano-sheet channel layers, in accordance with an embodiment of the present invention.

In one or more embodiments, the second masking layer **190** can be removed from one or more cut-stacks **155** after the portions of the nano-sheet channel layers **140** have been removed using a selective isotropic etch. The second masking layer **190** can be removed using processes known in the art (e.g., ashing, stripping, etc.). Removal of the second masking layer **190** can expose the previously masked cut-stack **155** for removal of a portion of the nano-sheet channel layers **140**. The indentation fill layers **180** can protect the ends of the sacrificial release layers **130** during subsequent etching of the nano-sheet channel layers **140**.

In one or more embodiments, additional portions of the one or more exposed nano-sheet channel layer(s) **140** can be removed from previously etched nano-sheet channel layer(s) using a second timed isotropic etch, for example, a wet etch or dry plasma etch, where the etchant can enter into the recesses **145** formed by the first etch. Additional etching steps may be used to remove additional material from one or more exposed cut-stacks **155**. In various embodiments, the isotropic etch selectively removes nano-sheet channel layer material not otherwise covered by the dummy gate **160**.

In one or more embodiments, portions of the one or more exposed nano-sheet channel layer(s) **140** can be removed from previously unetched cut-stacks **155**, where the nano-sheet channel layer(s) are exposed by removal of the second mask **190**, while nano-sheet channel layer(s) **140** of still masked cut-stack **155** can remain unaffected by the second and any subsequent etching steps.

The duration of the timed etch may be selected to remove a predetermined amount of nano-sheet channel layer material from each exposed recess **145**, so the depth of the recess

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increases by the predetermined amount for all exposed nano-sheet channel layers **140**. For example, an etch process that removes 1 nm of nano-sheet channel layer material per minute can be conducted for 2 minutes to increase the depth of the recesses **145** by 2 nm. The cut-stacks **155** that had previously undergone a 2 minute etch would therefore have recesses **145** that are 4 nm in depth, whereas the cut-stack that only underwent the second etch would have recesses with a 2 nm depth.

In various embodiments, the mask **190** can be removed from one or more of the still masked cut-stacks **155** subsequent to the second etch, and a third timed etch may be used to remove additional material from both the previously masked cut-stack and the exposed cut-stack to achieve three different predetermined etch depths for the recesses **145**. The process can be repeated to prepare multiple cut-stacks **155** with different recess depths on the substrate **110**. The recess depth can be greater than the indentation depth for at least one cut-stack **155**.

In various embodiments, the mask(s) **190** can be removed from different cut-stacks **155** after a predetermined number of etching steps to expose previously unetched nano-sheet channel layer(s) **140**, and masks **190** can be formed on previously etched nano-sheet channel layer(s) **140** to prevent further etching to thereby control the final recess depth of each of a plurality of cut-stacks **155** on a substrate **110**. Additional etching steps may be used to remove additional material from the nano-sheet channel layers **140** of one or more exposed cut-stacks **155**.

FIG. **12** is a cross-sectional side view of two cut-stacks having different sized recesses formed in the nano-sheet channel layers, in accordance with an embodiment of the present invention.

In one or more embodiments, the nano-sheet channel layers **140** can have a length in the range of about 15 nm to about 25 nm, or in the range of about 15 nm to about 20 nm, or in the range of about 19 nm to about 25 nm, although other lengths are also contemplated. In various embodiments, the nano-sheet channel layers of two different devices can have a difference in length in the range of about 2 nm to about 10 nm, or in the range of about 4 nm to about 10 nm, or in the range of about 2 nm to about 5 nm. In a non-limiting exemplary embodiment, the nano-sheet channel layers **140** of a first nano-sheet device can have a length in the range of about 15 nm to about 19 nm, and the nano-sheet channel layers **140** of a second nano-sheet device can have a length in the range of about 20 nm to about 25 nm, where the shorter nano-sheet channel layers can provide faster devices and the longer nano-sheet channel layers can provide devices with lower leakage current. In various embodiments, the recesses **145** can extend below the dummy gate fill **167** and side spacer **163**, where the isotropic etch selectively removed nano-sheet channel layer material.

Different V_{TS} s can be achieved by laterally undercutting the nano-sheet channel layers **140** in different cut-stacks **155** by different amounts. The source and drain of each nano-sheet device can then be formed on the endwalls of the recessed nano-sheet channel layers **140** by in-situ doped epitaxy. As a result, the nano-sheet devices can have about the same physically gate length, L_G , but different electrical gate length, L_{Ge} , due to different extents of lateral undercutting that reduces at least one lateral dimension (e.g., length) of the nano-sheet channel layers **140** to form the recesses **145**.

FIG. **13** is a cross-sectional side view of source/drains formed on the nano-sheet channel layers on either side of

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each of the two cut-stacks, in accordance with an embodiment of the present invention.

In one or more embodiments, a source/drain (S/D) regions **200** can be formed on the nano-sheet channel layers **140**, where the source/drain regions **200** can be formed by an epitaxial growth process on exposed crystalline faces of the nano-sheet channel layers **140**. The source/drain regions **200** can be in physical and electrical contact with each of the one or more nano-sheet channel layer(s) **140** in the cut-stack **155**.

In various embodiments, the source/drain region(s) **200** can be silicon or silicon-germanium suitably doped to form an n-type or a p-type field effect transistor (nFET or pFET). The S/D region(s) can be doped in situ (i.e. during formation).

FIG. **14** is a cross-sectional side view of an interlayer dielectric formed on the two cut-stacks and dummy gates, in accordance with an embodiment of the present invention.

In one or more embodiments, an interlayer dielectric (ILD) **210** can be formed on the source/drain region(s) **200**. The interlayer dielectric (ILD) **210** can be formed by a blanket deposition that covers the source/drain region(s) **200**, as well as portions of the dummy gate(s) **160**, substrate insulator layer **120**, and/or substrate surface. The interlayer dielectric (ILD) **210** can extend above the top surface of the dummy gates **160**, and chemical-mechanical polishing (CMP) can be utilized to remove the excess material and provide a smooth, flat surface.

In various embodiments, the interlayer dielectric (ILD) **210** can be silicon oxide or a low-k dielectric, where the ILD can be formed by CVD, LPCVD, or spun on. In various embodiments, a low-k dielectric material can be a fluoride-doped silicon oxide (e.g., fluoride doped glass), a carbon-doped silicon oxide, a porous silicon oxide, a spin-on silicon based polymeric material (e.g., tetraethyl orthosilicatehydrogen (TEOS), silsesquioxane (HSQ) and methylsilsesquioxane (MSQ)), or combinations thereof.

FIG. **15** is a cross-sectional side view of an interlayer dielectric on the two cut-stacks after removal of the dummy gate fills, in accordance with an embodiment of the present invention.

In one or more embodiments, the dummy gate fill **167** of the dummy gate(s) **160** can be removed to expose the underlying cut-stack **155**, where the dummy gate fill can be selectively removed. Selective removal of the dummy gate fill **167** can expose at least a portion of the underlying sacrificial release layer(s) **130**, and nano-sheet channel layer(s) **140**. Removal of the dummy gate fill **167** may also expose at least a portion of the indentation fill layer **180** directly below the side spacer **163**. The side spacer **163** can remain around at least a portion of the cut-stack **155** to provide a defined opening **220** for formation of an active gate structure.

In one or more embodiments, the dummy gate fill **167** can be removed by an isotropic etch, for example, a wet etch, that is selective for the material of the dummy gate fill **167** relative to the side spacer **163**, sacrificial release layer(s) **130**, and nano-sheet channel layers **140**.

FIG. **16** is a cut-away isometric view of the long axis of the patterned nano-sheet device after removing the dummy gate fill from within the side spacer, in accordance with an embodiment of the present invention.

As illustrated, the side spacer **163** can remain around at least a portion of the cut-stack **155** to provide a defined opening **220** for formation of an active gate structure, where a portion of the side spacer **163** has been cut away to show the opening formed by removal of the dummy gate fill **167**

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and the underlying cut-stack **155**. Only portions of the ILD **210** on the source/drain regions **200** are shown. The ILD **210** can surround the source/drain regions **200** and side spacer **163**. The dummy gate **160** can surround three sides of the patterned channel stack **150**, and subsequent cut-stack **155**.

FIG. **17** is a cross-sectional side view of a plurality of freed nano-sheet channel layers after removal of the intervening sacrificial release layers in the two cut-stacks, in accordance with an embodiment of the present invention.

In one or more embodiments, the remaining portions of the sacrificial release layer(s) **130** of the cut-stack(s) **155** can be removed to release the nano-sheet channel layer(s) **140**, where the nano-sheet channel layer(s) **140** can be secured at the opposite end faces **142** to the source/drain regions **200** formed in the recess(es) **145**. The indentation fill layer **180** can be between the source/drain regions **200** in the recess(es) **145**. The nano-sheet channel layer(s) **140** can span the distance between the two source/drain regions **200** on opposite sides of the dummy gate. Removal of the sacrificial release layer(s) can form air gaps **139** between the nano-sheet channel layer(s) **140**, where the nano-sheet channel layer(s) **140** can be exposed on the four sides not in direct contact with the source/drain regions **200** at opposite end faces **142**.

In one or more embodiments, the sacrificial release layer(s) **130** can be removed using an isotropic etch, for example, a wet etch selective for the material of the sacrificial release layer(s) **130**. In various embodiments, the etchant can be introduced into the opening **220**, such that the etchant can access the sides of the cut-stack **155** including the sidewalls of the sacrificial release layer(s) **130**. In various embodiments, a sacrificial release layer **130** is between the substrate insulator layer **120** and the lower-most nano-sheet channel layer **140**, so a subsequently formed gate electrode (i.e., work function layer and gate fill layer) can wrap around the lower-most nano-sheet channel layer **140**.

FIG. **18** is a cross-sectional side view of a gate dielectric layer on the exposed surfaces of the nano-sheets, in accordance with an embodiment of the present invention.

In one or more embodiments, a gate dielectric layer **230** can be formed on the exposed surfaces of the nano-sheet channel layer(s) **140**, where the gate dielectric layer **230** can be formed by a conformal deposition process, for example, ALD, CVD, or combinations thereof. In various embodiments, the precursors for the gate dielectric layer **230** can be selected based on the ability of entering the spaces formed between the nanosheet channel layer(s) **140** vacated by the sacrificial release layer(s) **130**. In one or more embodiments, the precursors for the gate dielectric layer **230** can be introduced into the opening(s) **220**.

In one or more embodiments, the gate dielectric layer **230** can be formed on the exposed surfaces of the substrate insulator layer **120** on opposite sides of the cut-stack **155** at the bottom of the opening **220** within the side spacer **163**. The gate dielectric layer **230** can also be formed on the inside surfaces of the side spacer **163**.

In one or more embodiments, the gate dielectric layer **230** can be an insulating dielectric layer, for example, a silicon oxide (SiO), silicon nitride (SiN), silicon oxynitride (SiON), a high-K dielectric, or a suitable combination of these materials.

In various embodiments, the gate dielectric layer **230** can be a high-K dielectric material that can include, but is not limited to, transition metal oxides such as hafnium oxide (e.g., HfO₂), hafnium silicon oxide (e.g., HfSiO₄), hafnium silicon oxynitride (Hf_wSi_xO_yN_z), lanthanum oxide (e.g., La₂O₃), lanthanum aluminum oxide (e.g., LaAlO₃), zirco-

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niun oxide (e.g., ZrO₂), zirconium silicon oxide (e.g., ZrSiO₄), zirconium silicon oxynitride (Zr_wSi_xO_yN_z), tantalum oxide (e.g., TaO₂, Ta₂O₅), titanium oxide (e.g., TiO₂), barium strontium titanium oxide (e.g., BaTiO₃—SrTiO₃), barium titanium oxide (e.g., BaTiO₃), strontium titanium oxide (e.g., SrTiO₃), yttrium oxide (e.g., Y₂O₃), aluminum oxide (e.g., Al₂O₃), lead scandium tantalum oxide (Pb(Sc_xTa_{1-x})O₃), and lead zinc niobate (e.g., PbZn_{1/3}Nb_{2/3}O₃). The high-k material can further include dopants such as lanthanum and/or aluminum. The stoichiometry of the high-K compounds can vary.

In one or more embodiments, a work function layer **240** can be formed on the gate dielectric layer **230**, where the work function layer and gate dielectric layer **230** can surround at least a portion of each of the one or more nano-sheet channel layer(s) **140**. A work function layer **240** can be formed on the exposed portion(s) of the gate dielectric layer **230** between the nano-sheet channel layer(s) **140**. The work function layer **240** can be formed on the gate dielectric layer **230** to adjust the electrical properties of a gate electrode. In various embodiments, the work function layer can be optional. A portion of the work function layer **240** can be formed on the gate dielectric layer **230** on the substrate insulator layer **120** beneath the bottom-most nano-sheet channel layer **140**.

In one or more embodiments, the work function layer **240** can fill in the spaces between the gate dielectric layer **230** on the nanosheet channel layer(s) **140**. The work function layer can be formed by a conformal deposition, for example, ALD.

In various embodiments, a work function layer **240** can be a conductive nitride, including but not limited to titanium nitride (TiN), titanium aluminum nitride (TiAlN), hafnium nitride (HfN), hafnium silicon nitride (HfSiN), tantalum nitride (Ta₂N), tantalum silicon nitride (TaSiN), tungsten nitride (WN), molybdenum nitride (MoN), niobium nitride (NbN); a conductive carbide, including but not limited to titanium carbide (TiC), titanium aluminum carbide (TiAlC), tantalum carbide (TaC), hafnium carbide (HfC); or combinations thereof. The work function layer **240** can include multiple layers of work function materials, for example, a work function layer can be a TiN/TiC stack.

In various embodiments, the work function layer **240** can have a thickness in the range of about 3 nm to about 11 nm, or can have a thickness in the range of about 5 nm to about 8 nm.

FIG. **19** is a cross-sectional side view of a gate structure on each of the cut-stacks, in accordance with an embodiment of the present invention.

In one or more embodiments, a gate fill layer **250** can be formed on the gate dielectric layer **230** and/or work function layer **240** if present, where the gate fill layer **250** can fill in the space of opening **220** in between side spacers **163**. The gate fill layer **250**, gate dielectric layer **230**, and optionally the work function layer **240**, can form a gate structure on one or more nano-sheet channel layer(s) **140**, where the gate fill layer **250** and work function layer **240** can form a conductive gate electrode.

In various embodiments, the gate fill layer **250** can be blanket deposited on the exposed surfaces of the gate dielectric layer **230** and/or work function layer **240**. The formed gate fill layer **250** can extend above the top surface of the interlayer dielectric **210**, where the gate fill layer material above the top surfaces of the interlayer dielectric **210** can be removed by a CMP to provide a flat, uniform surface.

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In various embodiments, the gate fill layer **250** can be a conductive metal, where the metal can be tungsten (W), titanium (Ti), molybdenum (Mo), cobalt (Co), or a conductive carbon material (e.g., carbon nanotube, graphene, etc.), or any suitable combinations thereof.

In one or more embodiments, the gate dielectric layer **230** and the work function layer **240** can wrap around each of the nano-sheet channel layer(s) **140**, and the gate fill layer **250** can surround the nano-sheet channel layer(s) **140** and work function layer **240**. The gate dielectric layer **230** can extend up the inside surface of the side spacer **163**, and the interlayer dielectric (ILD) **210** can be on the outside surface of the sidewall spacer **163**.

In various embodiments, the width of the gate fill layer **250** or gate electrode at the top of the gate structure can be the same for both (or all) of the nano-sheet devices, whereas the width of the gate fill layer **250** at the bottom of the gate structure (adjacent to the top-most nano-sheet channel layer **140**) can be greater than the width at the top for one or more of the gate structure(s) and less than the width at the top for one or more other gate structure(s). In various embodiments, the overlap between the gate fill layer **250** or gate electrode at the bottom of the gate structure adjacent to the top-most nano-sheet channel layer **140** and the portion of the source/drain regions **200** extending into the recess **145** can be the same, such that the overlap capacitance, C_{ov} , of both nano-sheet devices is essentially the same (e.g., within process control tolerances), while the electrical gate lengths, L_{Ge} , and threshold voltage, V_T , are different for each nano-sheet device. The overlap can be measured between the source/drain region **200** and the bottom area of the gate electrode. The lengths of the indentation fill layer **180** can adjust for the difference in the lengths of the nano-sheet channel layer(s) **140** of two different devices. Nano-sheet transistor devices can thereby be fabricated with the same physical gate length, L_G , but with different electrical gate lengths, L_{Ge} , and resulting threshold voltages, V_T . For a CMOS technology, transistors with different threshold voltages, V_T , could achieve optimal tradeoff between performance and power consumption.

In various embodiments, electrical contacts can be formed to the gate structure and source/drain regions **200** for electrically connecting the nano-sheet devices.

It will also be understood that when an element such as a layer, region or substrate is referred to as being “on” or “over” another element, it can be directly on the other element or intervening elements may also be present. In contrast, when an element is referred to as being “directly on” or “directly over” another element, there are no intervening elements present. It will also be understood that when an element is referred to as being “connected” or “coupled” to another element, it can be directly connected or coupled to the other element or intervening elements may be present. In contrast, when an element is referred to as being “directly connected” or “directly coupled” to another element, there are no intervening elements present.

It should be understood that use of descriptions such as top, bottom, left, right, vertical, horizontal, or the like, are intended to be in reference to the orientation(s) illustrated in the figures, and are intended to be descriptive and to distinguish aspects of depicted features without being limiting. Spatially relative terms, such as “beneath,” “below,” “lower,” “above,” “upper,” and the like, may be used herein for ease of description to describe one element’s or feature’s relationship to another element(s) or feature(s) as illustrated in the FIGs. It will be understood that the spatially relative terms are intended to encompass different orientations of the

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device in use or operation in addition to the orientation depicted in the FIGs. For example, if the device in the FIGs. is turned over, elements described as “below” or “beneath” other elements or features would then be oriented “above” the other elements or features. Thus, the term “below” can encompass both an orientation of above and below. The device may be otherwise oriented (rotated 90 degrees or at other orientations), and the spatially relative descriptors used herein may be interpreted accordingly. In addition, it will also be understood that when a layer is referred to as being “between” two layers, it can be the only layer between the two layers, or one or more intervening layers may also be present.

It will be understood that, although the terms first, second, etc. may be used herein to describe various elements, these elements should not be limited by these terms. These terms are only used to distinguish one element from another element. Reference to first, second, third, etc., feature is intended to distinguish features without necessarily implying a particular order unless otherwise so stated or indicated. Thus, a first element discussed herein could be termed a second element without departing from the scope of the present concept.

The present embodiments may include a design for an integrated circuit chip, which may be created in a graphical computer programming language, and stored in a computer storage medium (such as a disk, tape, physical hard drive, or virtual hard drive such as in a storage access network). If the designer does not fabricate chips or the photolithographic masks used to fabricate chips, the designer may transmit the resulting design by physical means (e.g., by providing a copy of the storage medium storing the design) or electronically (e.g., through the Internet) to such entities, directly or indirectly. The stored design is then converted into the appropriate format (e.g., GDSII) for the fabrication of photolithographic masks, which typically include multiple copies of the chip design in question that are to be formed on a wafer. The photolithographic masks are utilized to define areas of the wafer (and/or the layers thereon) to be etched or otherwise processed.

Methods as described herein may be used in the fabrication of integrated circuit chips. The resulting integrated circuit chips can be distributed by the fabricator in raw wafer form (that is, as a single wafer that has multiple unpackaged chips), as a bare die, or in a packaged form. In the latter case the chip is mounted in a single chip package (such as a plastic carrier, with leads that are affixed to a motherboard or other higher level carrier) or in a multichip package (such as a ceramic carrier that has either or both surface interconnections or buried interconnections). In any case the chip is then integrated with other chips, discrete circuit elements, and/or other signal processing devices as part of either (a) an intermediate product, such as a motherboard, or (b) an end product. The end product can be any product that includes integrated circuit chips, ranging from toys and other low-end applications to advanced computer products having a display, a keyboard or other input device, and a central processor.

Reference in the specification to “one embodiment” or “an embodiment” of the present invention, as well as other variations thereof, means that a particular feature, structure, characteristic, and so forth described in connection with the embodiment is included in at least one embodiment of the present invention. Thus, the appearances of the phrase “in one embodiment” or “in an embodiment”, as well any other

variations, appearing in various places throughout the specification are not necessarily all referring to the same embodiment.

It is to be appreciated that the use of any of the following “/”, “and/or”, and “at least one of”, for example, in the cases of “A/B”, “A and/or B” and “at least one of A and B”, is intended to encompass the selection of the first listed option (A) only, or the selection of the second listed option (B) only, or the selection of both options (A and B). As a further example, in the cases of “A, B, and/or C” and “at least one of A, B, and C”, such phrasing is intended to encompass the selection of the first listed option (A) only, or the selection of the second listed option (B) only, or the selection of the third listed option (C) only, or the selection of the first and the second listed options (A and B) only, or the selection of the first and third listed options (A and C) only, or the selection of the second and third listed options (B and C) only, or the selection of all three options (A and B and C). This may be extended, as readily apparent by one of ordinary skill in this and related arts, for as many items listed.

Having described preferred embodiments of a device and fabrication method (which are intended to be illustrative and not limiting), it is noted that modifications and variations can be made by persons skilled in the art in light of the above teachings. It is therefore to be understood that changes may be made in the particular embodiments disclosed which are within the scope of the invention as outlined by the appended claims. Having thus described aspects of the invention, with the details and particularity required by the patent laws, what is claimed and desired protected by Letters Patent is set forth in the appended claims.

The invention claimed is:

1. A method of forming two or more nano-sheet devices with varying channel lengths, comprising:

forming at least two cut-stacks including a plurality of sacrificial release layers and at least one alternating nano-sheet channel layer on a substrate;

removing a portion of the plurality of sacrificial release layers to form indentations having an indentation depth in the plurality of sacrificial release layers;

removing a portion of the at least one alternating nano-sheet channel layer in a first of the at least two cut-stacks to form a first recess having a first recess depth in the at least one alternating nano-sheet channel layer; and

removing a portion of the at least one alternating nano-sheet channel layer in a second of the at least two cut-stacks to provide two different channel lengths.

2. The method of claim 1, further comprising forming the plurality of sacrificial release layers and the at least one alternating nano-sheet channel layer on the substrate by an epitaxially growth process, patterning and etching the plurality of sacrificial release layers and the at least one alternating nano-sheet channel layer to form a channel stack, and forming a dummy gate on the channel stack.

3. The method of claim 2, wherein the at least two cut-stacks are formed from the same channel stack.

4. The method of claim 1, further comprising forming a mask on at least one of the at least two cut-stacks after removing a portion of the plurality of sacrificial release layers, and removing an additional portion of the plurality of sacrificial release layers from the unmasked cut-stacks.

5. The method of claim 4, wherein the additional portion of the plurality of sacrificial release layers is removed using an isotropic wet etch.

6. The method of claim 1, further comprising [foaming] forming a mask on at least one of the at least two cut-stacks before removing a portion of the at least one alternating nano-sheet channel layer to form a recess in the unmasked cut-stacks.

7. The method of claim 6, further comprising removing the mask from the at least one of the at least two cut-stacks after removing a portion of the at least one alternating nano-sheet channel layer, and removing a portion of the at least one alternating nano-sheet channel layer to form a recess in the previously masked at least one of the at least two cut-stacks and an additional portion of the at least one alternating nano-sheet channel layer from the unmasked at least one of the at least two cut-stacks.

8. The method of claim 1, further comprising forming a source/drain on each of the at least two cut-stacks.

9. The method of claim 8, wherein the source/drains are epitaxially grown on the exposed surfaces of the at least one alternating nano-sheet channel layer.

10. A method of forming two or more nano-sheet devices with varying channel lengths, comprising:

forming a channel stack including a plurality of sacrificial release layers and at least one alternating nano-sheet channel layer on a substrate;

forming [at least] two or more cut-stacks from the channel stack, where each of the [at least] two or more cut-stacks includes a plurality of sacrificial release layers and at least one alternating nano-sheet channel layer;

removing a portion of the plurality of sacrificial release layers to form indentations having an indentation depth in the plurality of sacrificial release layers;

forming an indentation fill layer in the indentations;

forming a mask on at least one of the two or more cut-stacks; and

removing a portion of the at least one alternating nano-sheet channel layer to form a recess in the unmasked cut-stacks.

11. The method of claim 10, further comprising removing the mask from the at least one of the two or more cut-stacks after removing a portion of the at least one alternating nano-sheet channel layer, and removing a portion of the at least one alternating nano-sheet channel layer to form a recess in the previously masked at least one of the two or more cut-stacks and an additional portion of the at least one alternating nano-sheet channel layer from the at least one unmasked of the two or more cut-stacks.

12. The method of claim 11, further comprising forming a source/drain on each of the two or more cut-stacks.

13. The method of claim 12, further comprising forming a gate structure on each of the two or more cut-stacks.

14. A method of forming two or more nano-sheet devices with varying channel lengths, comprising:

forming at least two cut-stacks including a plurality of sacrificial release layers and at least one alternating nano-sheet channel layer on a substrate;

removing a portion of the plurality of sacrificial release layers to form indentations having an indentation depth in the plurality of sacrificial release layers; and

removing a portion of the at least one alternating nano-sheet channel layer to form a recess having a recess depth in the at least one alternating nano-sheet channel layer, wherein the one of the two or more nano-sheet devices has a different threshold voltage, V_T , than the other of the two or more nano-sheet devices by altering the length of the at least one alternating nano-sheet channel layer.

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15. The method of claim 14, wherein an isotropic etch forms the indentations having a predetermined indentation depth in the range of about 2 nm to about 10 nm.

16. The method of claim 14, wherein the sacrificial release layers have a thickness in the range of about 5 nm to about 20 nm.

17. The method of claim 14, wherein the sacrificial release layers are silicon-germanium (SiGe).

18. The method of claim 14, wherein the at least one alternating nano-sheet channel layer is epitaxially grown on a crystalline surface of the substrate.

19. The method of claim 14, wherein the at least one alternating nano-sheet channel layer is a single crystal silicon layer on a crystalline sacrificial release layer.

20. *A method of forming nano-sheet devices, the method comprising:*

providing at least two dummy gate structures, each of the dummy gate structures (i) disposed on a cut-stack comprising alternating sacrificial release layers and nano-sheet channel layers and (ii) comprising opposing side spacers, each side spacer having opposing inside and outside surfaces;

forming first lateral indentations of a first depth in a first plurality of sacrificial release layers of a first cut-stack; forming second lateral indentations of a second depth in a second plurality of sacrificial release layers of a second cut-stack, wherein the second depth is greater than the first depth; and

filling the first lateral indentations in the first cut-stack and the second lateral indentations in the second cut-stack with a dielectric material.

21. *The method of claim 20, further comprising:*

forming third lateral indentations to a third depth in sacrificial release layers of a third cut-stack, wherein the third depth is greater than the second depth.

22. *The method of claim 20, wherein the first depth is less than a distance between the opposing inside and outside surfaces of a side spacer of the first dummy gate structure.*

23. *The method of claim 20, wherein the second depth is greater than a distance between the opposing inside and outside surfaces of a side spacer of the second dummy gate structure.*

24. *The method of claim 20, wherein forming the second lateral indentations in the second cut-stack comprises:*

laterally etching sacrificial release layers of an unmasked second cut-stack.

25. *The method of claim 20, further comprising:*

subsequent to filling the first lateral indentations and the second lateral indentations, epitaxially growing a source/drain material on exposed faces of nano-sheet channel layers of the first cut-stack and the second cut-stack.

26. *The method of claim 25, further comprising:*

subsequent to epitaxially growing the source/drain material, replacing the dummy gate structures with active gate structures.

27. *The method of claim 20, wherein the first depth is in a range of about 2 nm and about 5 nm and second depth is in a range of about 5 nm and about 10 nm.*

28. *The method of claim 20, wherein an uppermost layer of the alternating sacrificial release layers and nano-sheet channel layers of a cut-stack is a sacrificial release layer.*

29. *The method of claim 20, wherein providing the at least two dummy gate structures comprises using a double patterning process.*

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30. *A method of forming nano-sheet devices comprising: providing at least two dummy gate structures, each of the dummy gate structures (i) disposed on a cut-stack comprising alternating sacrificial release layers and nano-sheet channel layers, (ii) comprising opposing side spacers, each side spacer having opposing inside and outside surfaces, the opposing inside surfaces being a distance apart, and (iii) having the distance between opposing inside surfaces being substantially the same;*

recessing end portions of first nano-sheet channel layers of a first cut-stack to a first depth;

recessing end portions of second nano-sheet channel layers of a second cut-stack to a second depth, wherein the second depth is greater than the first depth;

forming source/drain regions contacting each of the first and second nano-sheet channel layers; and

replacing the dummy gate structures with active gate structures.

31. *The method of claim 30, further comprising:*

recessing end portions of third nano-sheet channel layers of a third cut-stack to a third depth, wherein the third depth is greater than the second depth.

32. *The method of claim 30, wherein recessing end portions of the second nano-sheet channel layers comprises: laterally etching nano-sheet channel layers of an unmasked second cut-stack.*

33. *The method of claim 30, wherein the first and second cut-stacks comprise nano-sheet channel layers of a length in a range of about 19 nm and about 25 nm.*

34. *The method of claim 30, wherein a difference between a first length of the first nanosheet channel layers of the first cut-stack and a second length of the second nanosheet channel layers of the second cut-stack is in a range of about 2 nm to about 5 nm.*

35. *The method of claim 30, wherein a distance separating opposing source/drain regions of the first cut-stack is greater than a distance separating opposing source/drain regions of the second cut-stack.*

36. *The method of claim 30, wherein an uppermost layer of the alternating sacrificial release layers and nano-sheet channel layers is a sacrificial release layer.*

37. *The method of claim 30, wherein providing the at least two dummy gate structures comprises using a double patterning process.*

38. *The method of claim 30, further comprising:*

prior to recessing the end portions of the first nano-sheet channel layers of the first cut-stack:

forming first lateral indentations to a third depth in the sacrificial release layers of the first cut-stack; and

forming second lateral indentations to a fourth depth in the sacrificial release layers of the second cut-stack, wherein the fourth depth is greater than the third depth.

39. *The method of claim 38, further comprising:*

filling the first lateral indentations in the first cut-stack and the second lateral indentations in the second cut-stack with a dielectric material.

40. *A method of forming nano-sheet devices comprising:*

providing at least two dummy gate structures, each of the dummy gate structures (i) disposed on cut-stacks comprising alternating sacrificial release layers and nano-sheet channel layers, (ii) comprising opposing side spacers, each side spacer having opposing inside and outside surfaces, the opposing inside surfaces being a distance apart, and (iii) having the distance between opposing inside surfaces being substantially the same;

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recessing end portions of a plurality of nano-sheet chan-
nel layers of a first cut-stack to a first depth;
recessing end portions of a plurality of nano-sheet chan-
nel layers of a second cut-stack to a second depth,
wherein the second depth is greater than the first depth; 5
forming source/drain regions contacting each of the plu-
rality of first and second nano-sheet channel layers,
wherein a distance separating opposing source/drain
regions of the first cut-stack is greater than a distance
separating opposing source/drain regions of the second 10
cut-stack;
replacing the dummy gate structures with active gate
structures.

41. The method of claim 40, further comprising:
recessing end portions of a plurality of nano-sheet chan- 15
nel layers of a third cut-stack to a third depth, wherein
the third depth is greater than the second depth.

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