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(19) **United States**(12) **Patent Application Publication**
Nandakumar et al.(10) **Pub. No.: US 2025/0267930 A1**(43) **Pub. Date: Aug. 21, 2025**(54) **SEMICONDUCTOR DEVICE WITH LOW
NOISE TRANSISTOR AND LOW
TEMPERATURE COEFFICIENT RESISTOR**(52) **U.S. Cl.**CPC *H10D 84/811* (2025.01); *H10D 84/013*
(2025.01); *H10D 84/0135* (2025.01); *H10D*
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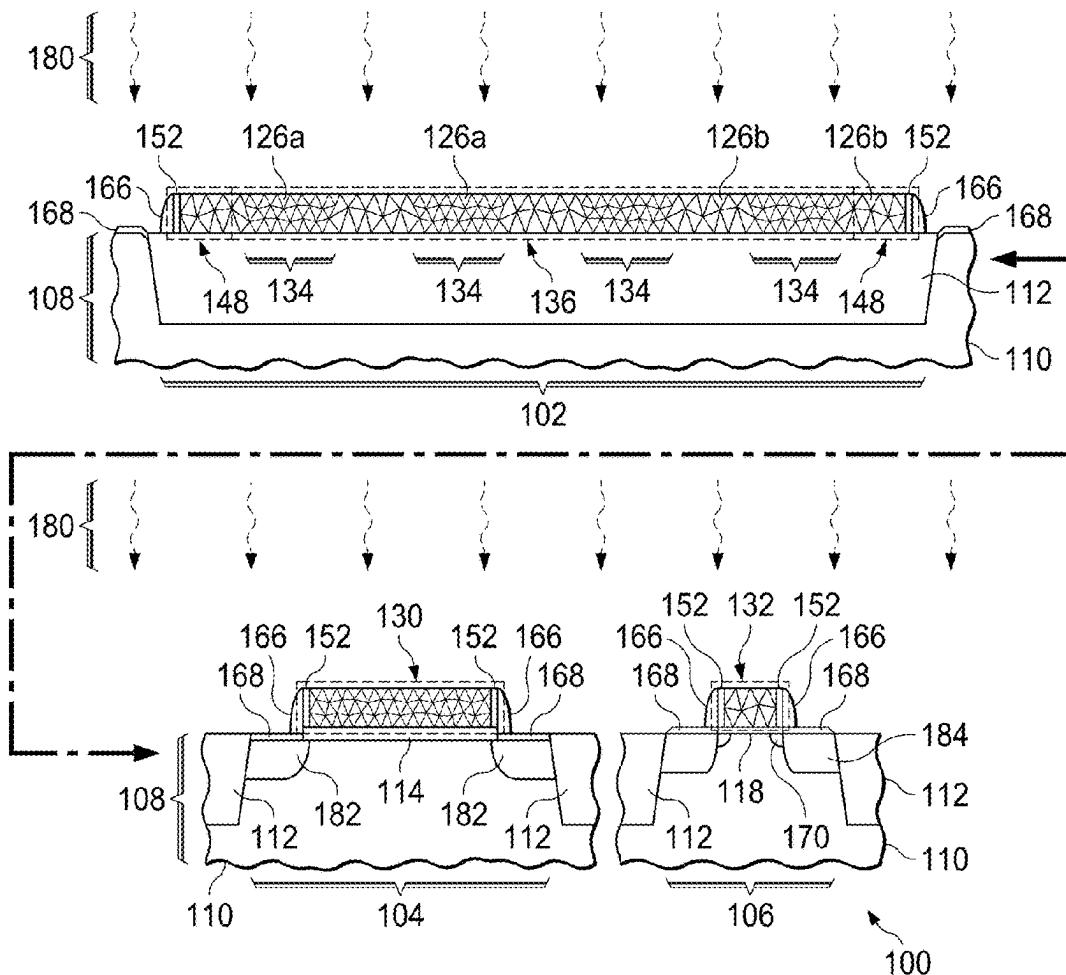
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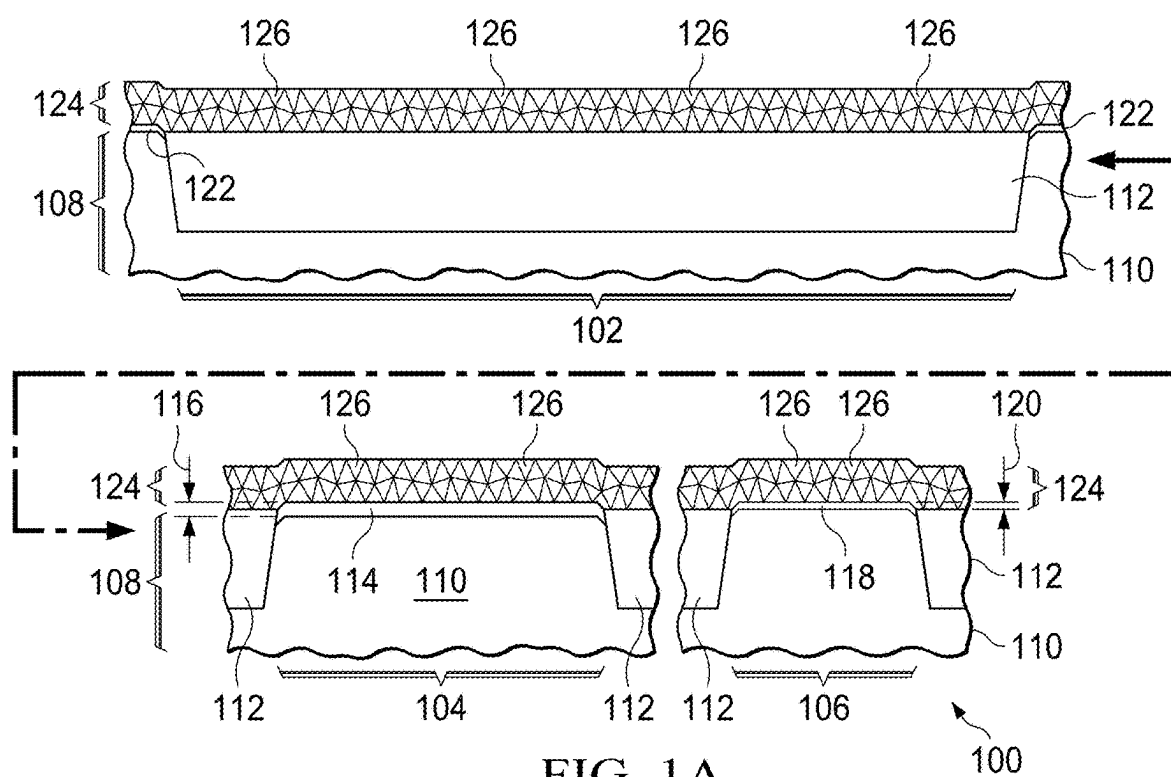
ABSTRACT

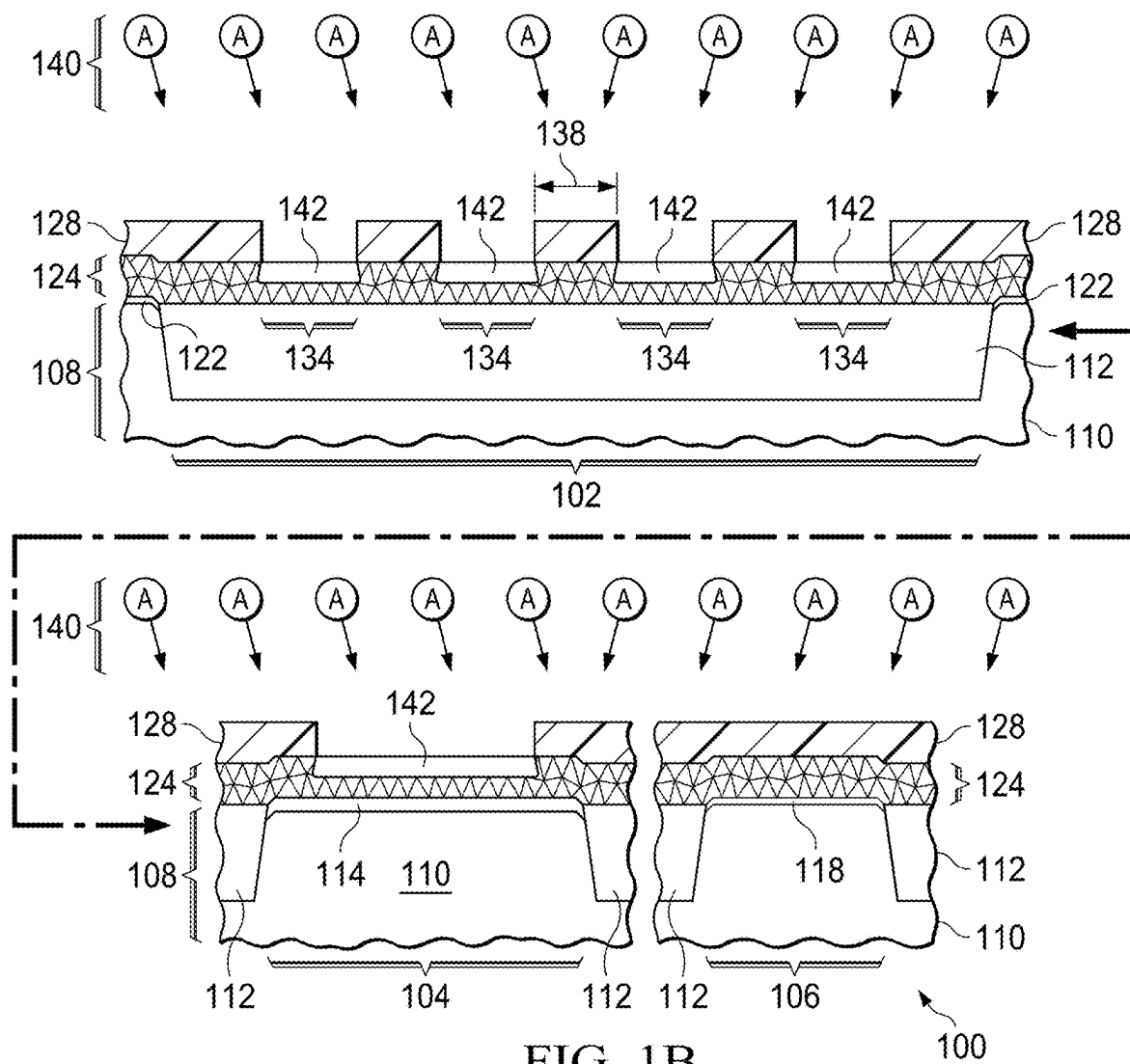
A semiconductor device includes a resistor having a resistor body including polysilicon, with fluorine in the polysilicon. The resistor body has a laterally alternating distribution of silicon grain sizes. The semiconductor device further includes an MOS transistor having a gate including polysilicon with fluorine. The fluorine in the gate has a higher average concentration than the fluorine in the resistor body. The semiconductor device may be formed by forming a gate/resistor layer including polysilicon. A fluorine implant mask is formed over the gate/resistor layer, exposing the gate/resistor layer in an area for the gate and over implant segments in an area for the resistor body. The implant segments do not cover the entire area for the resistor body. Fluorine is implanted into the gate/resistor layer where exposed by the fluorine implant mask. The gate/resistor layer is patterned to form the gate and the resistor body.

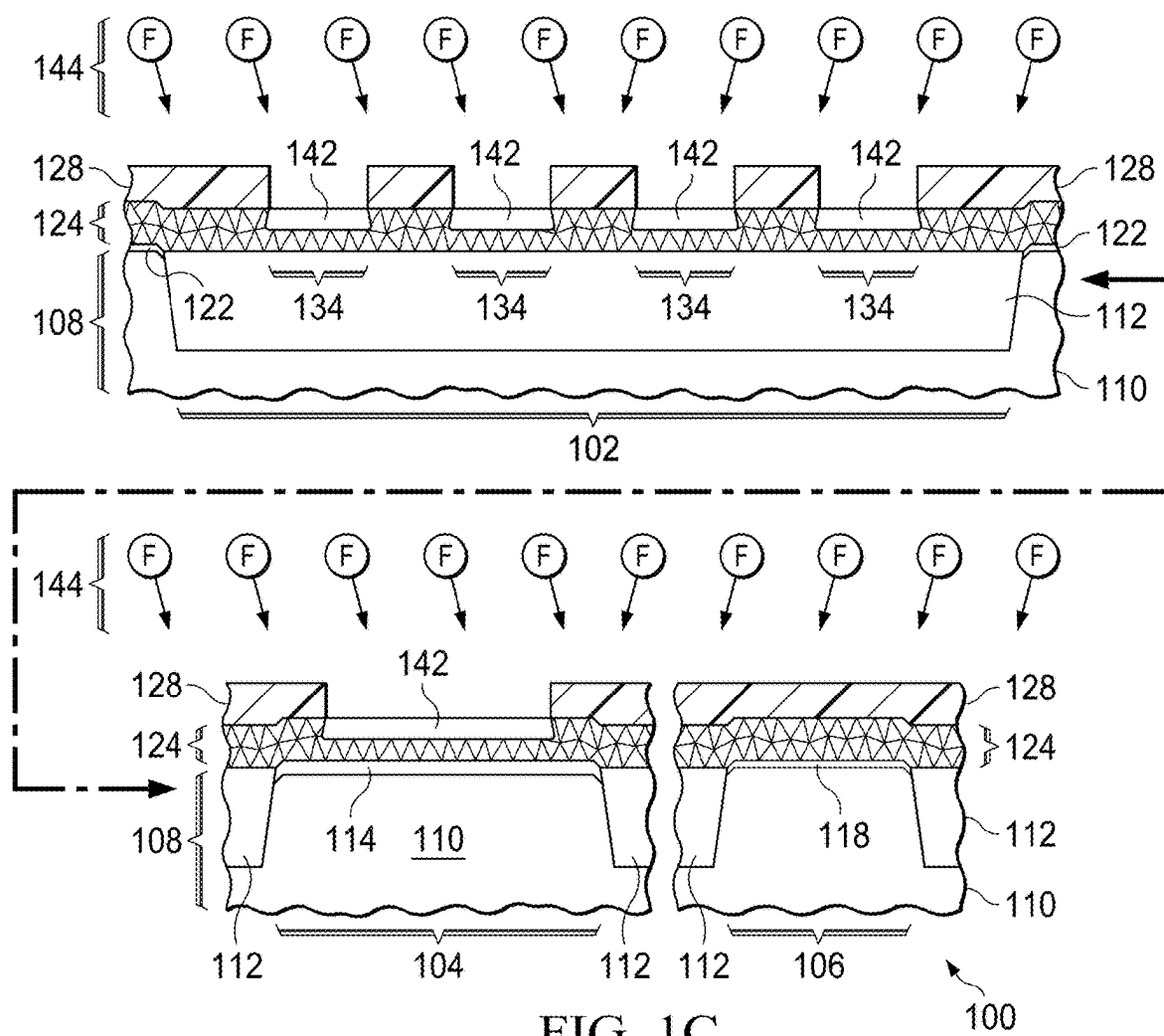
(21) Appl. No.: **19/193,469**(22) Filed: **Apr. 29, 2025****Related U.S. Application Data**

(63) Continuation of application No. 18/317,227, filed on May 15, 2023, now Pat. No. 12,317,583, which is a continuation of application No. 17/086,421, filed on Nov. 1, 2020, now Pat. No. 11,676,961.

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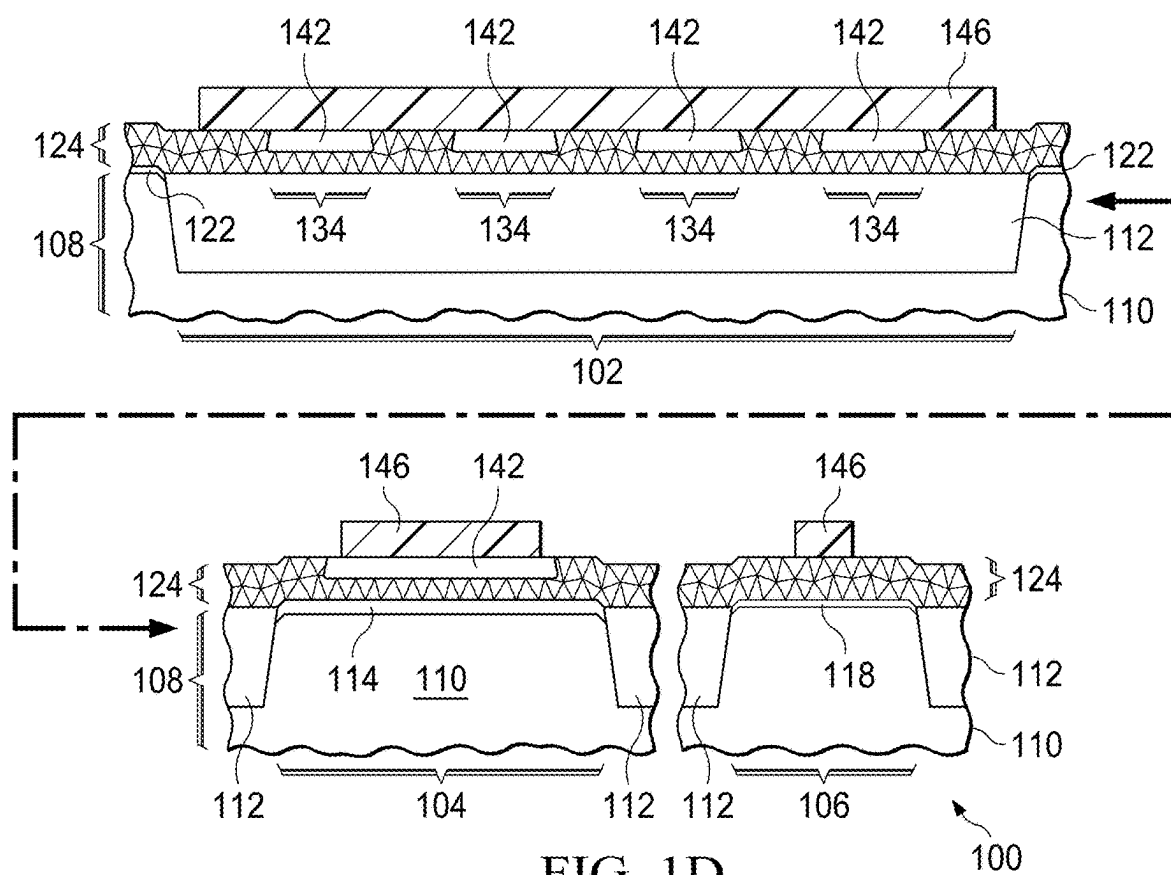
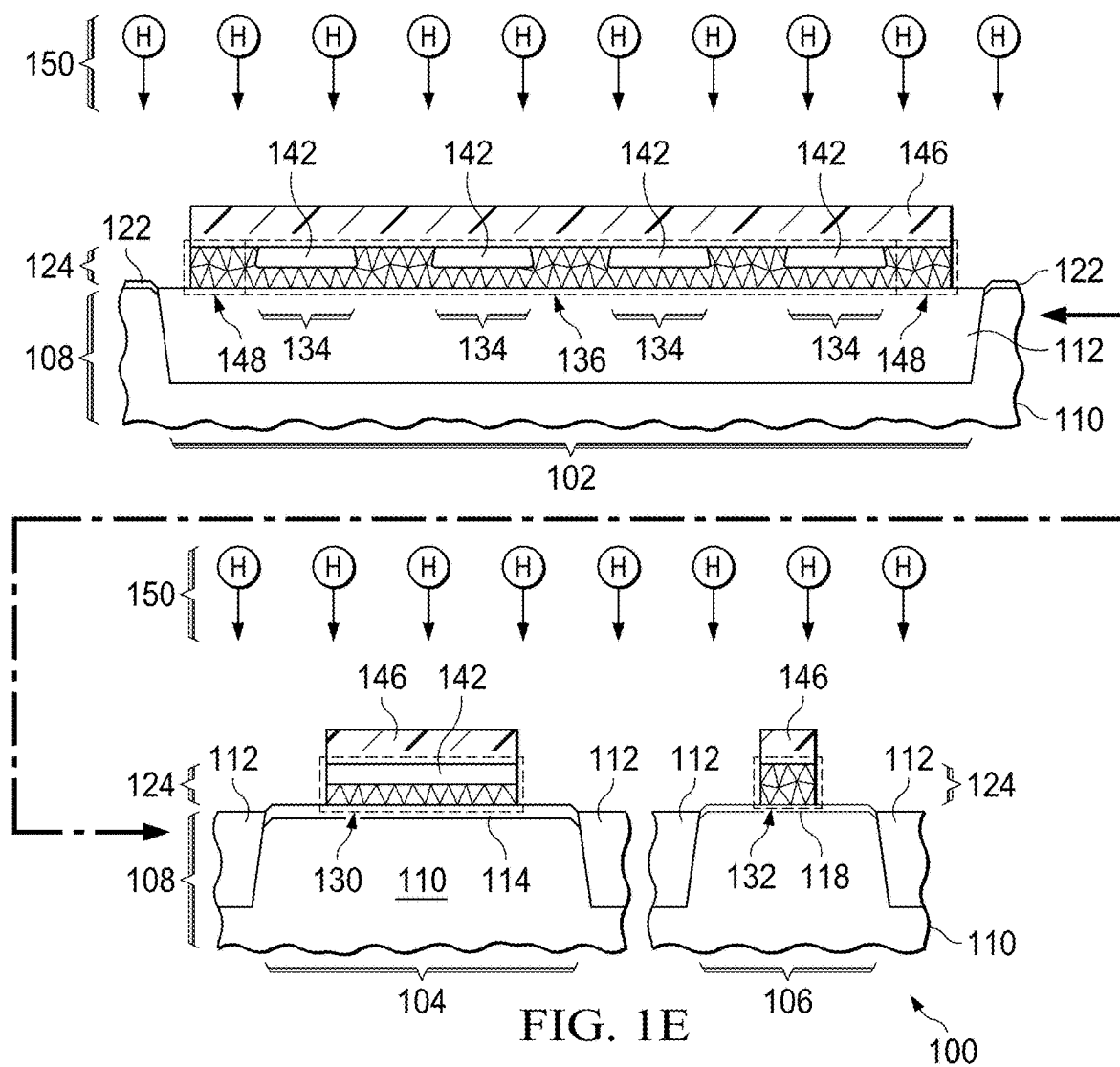
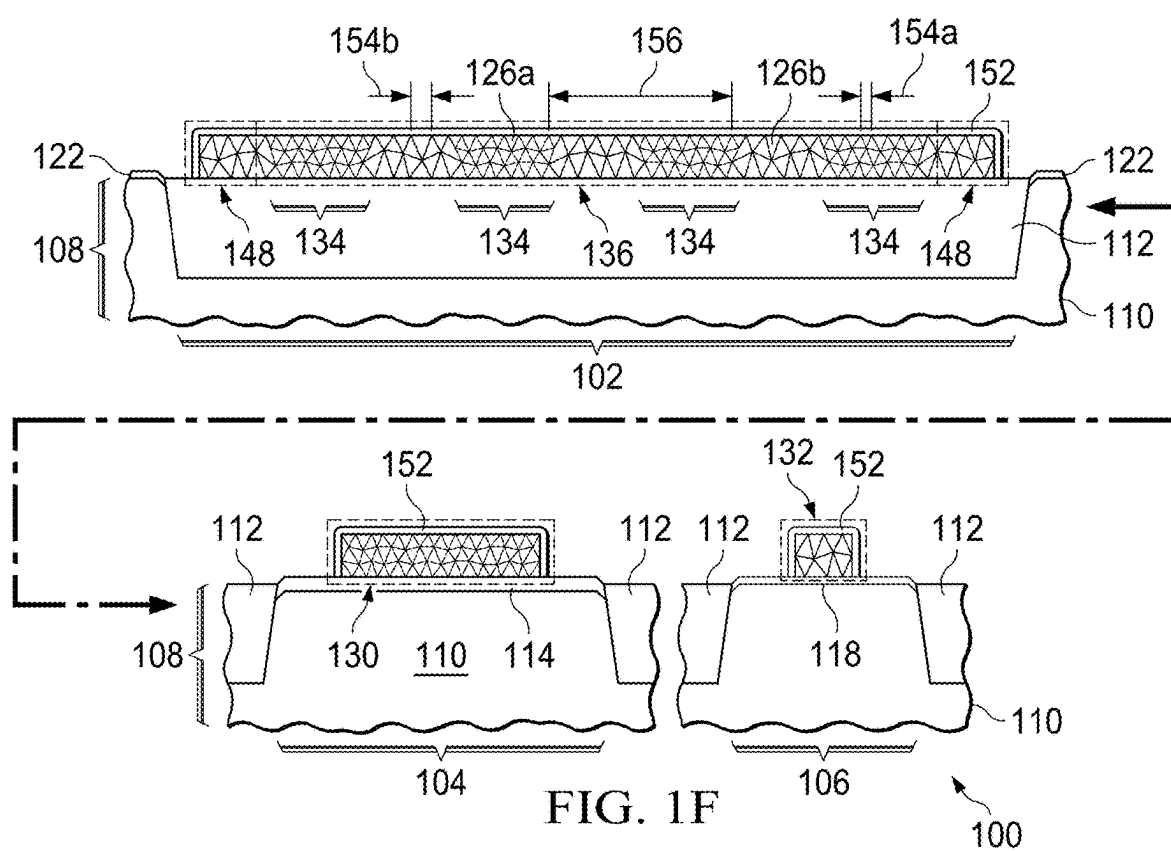
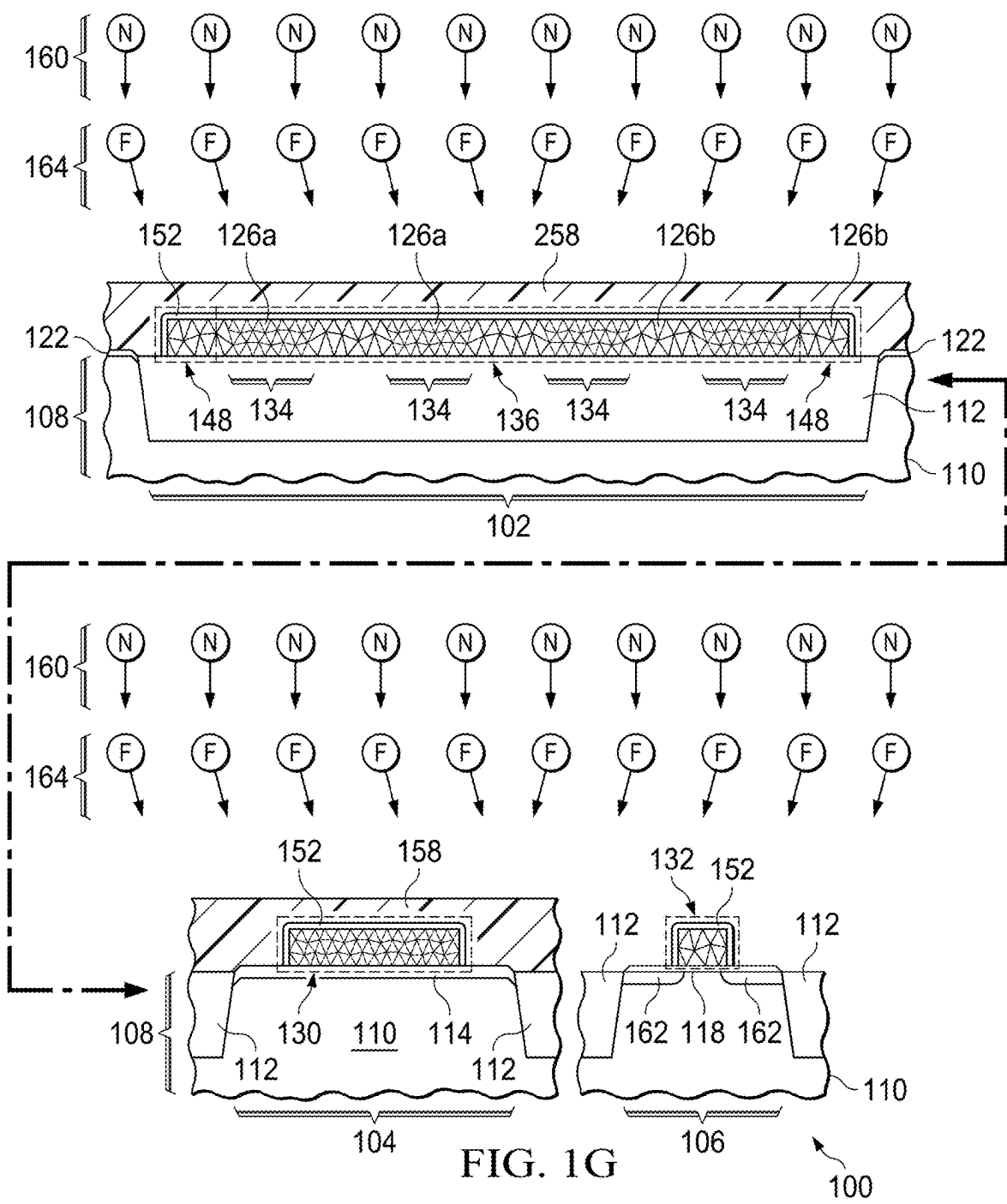


FIG. 1D







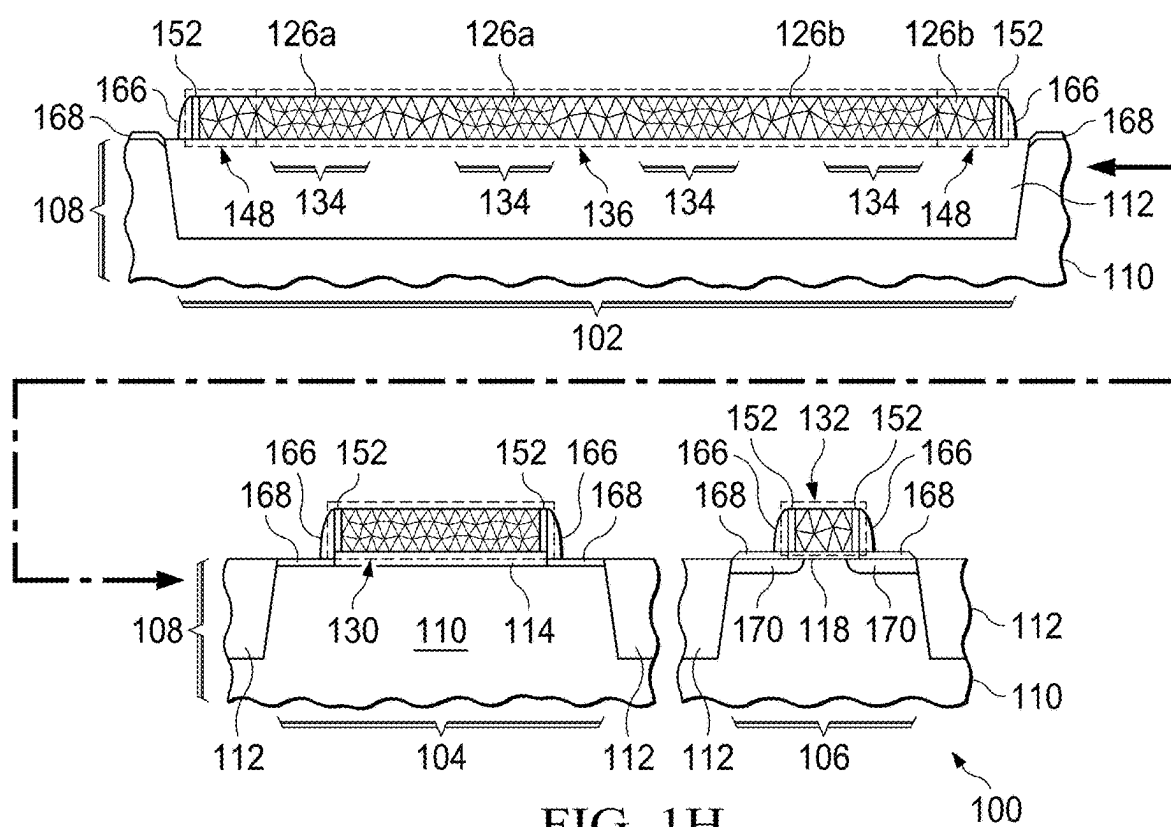
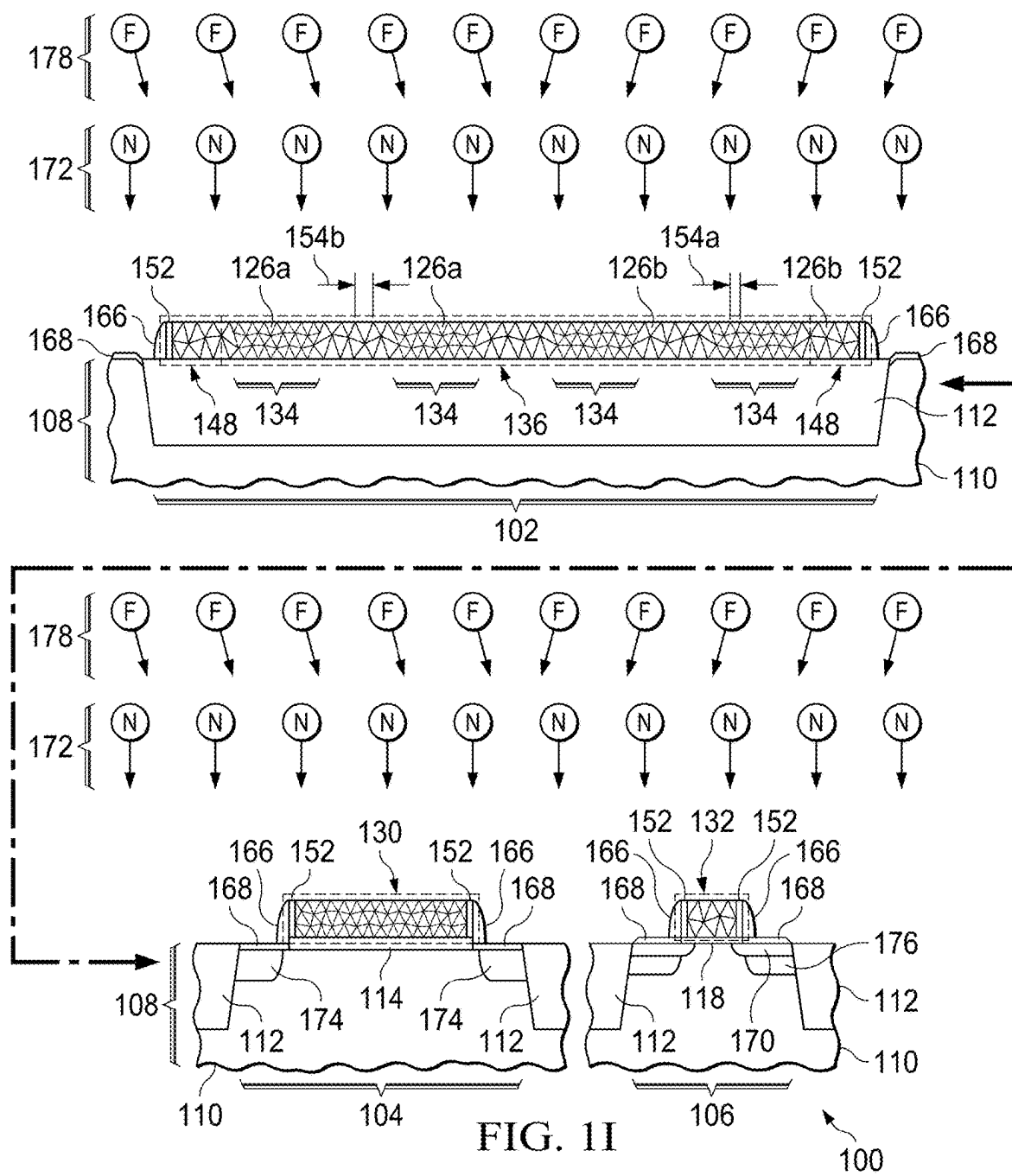
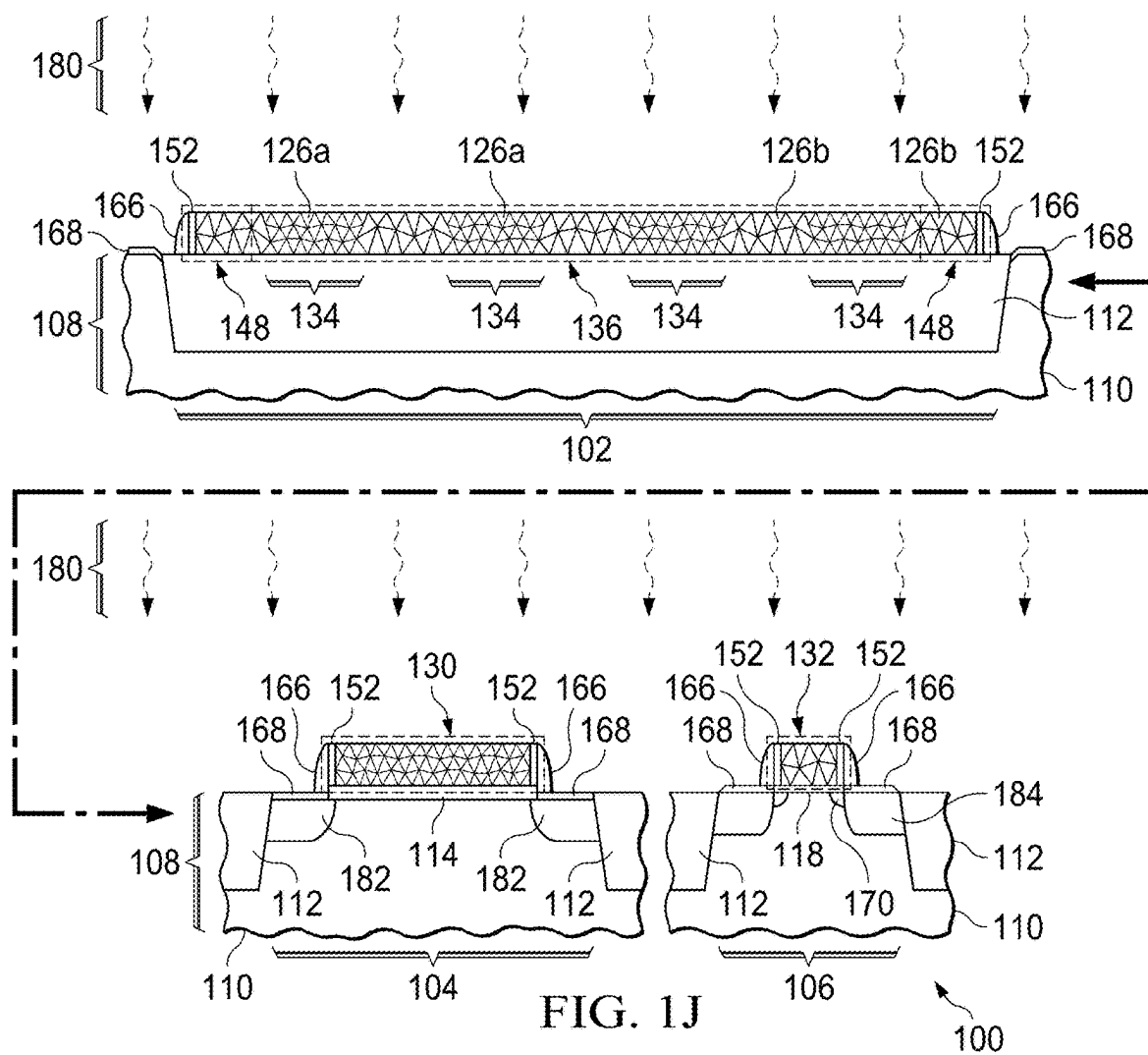
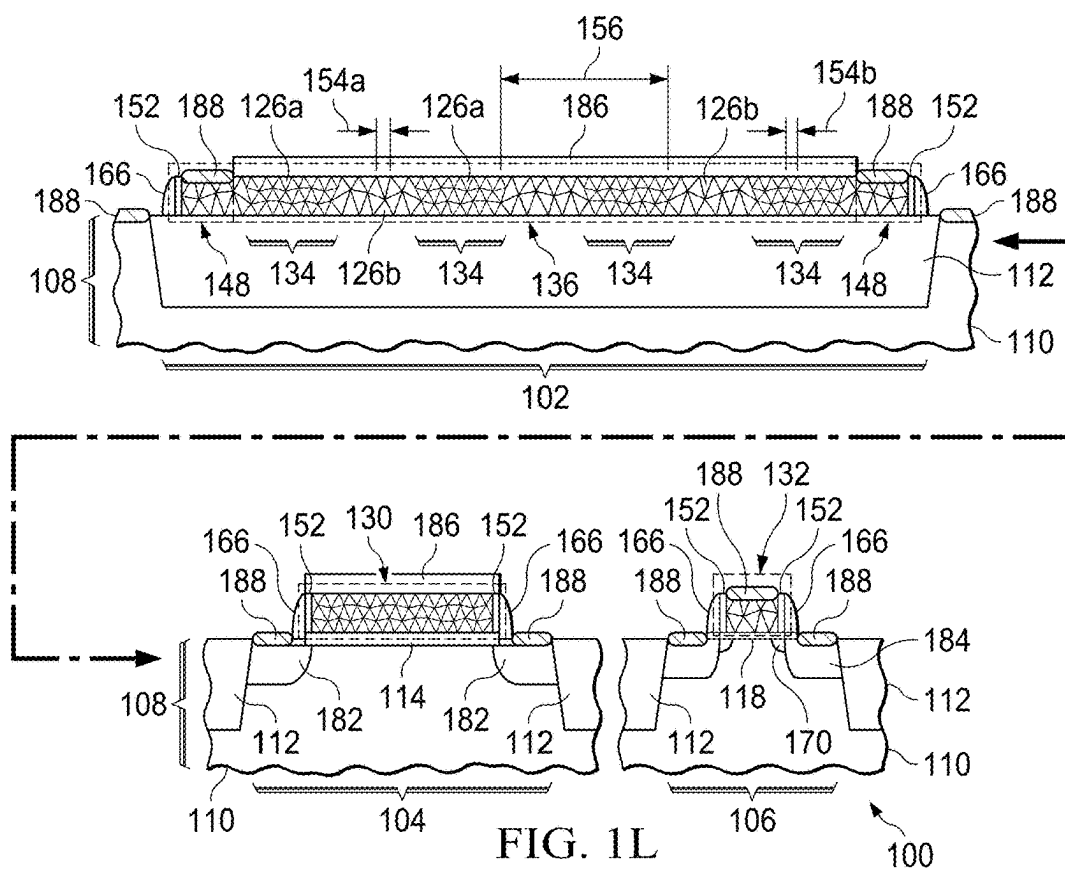
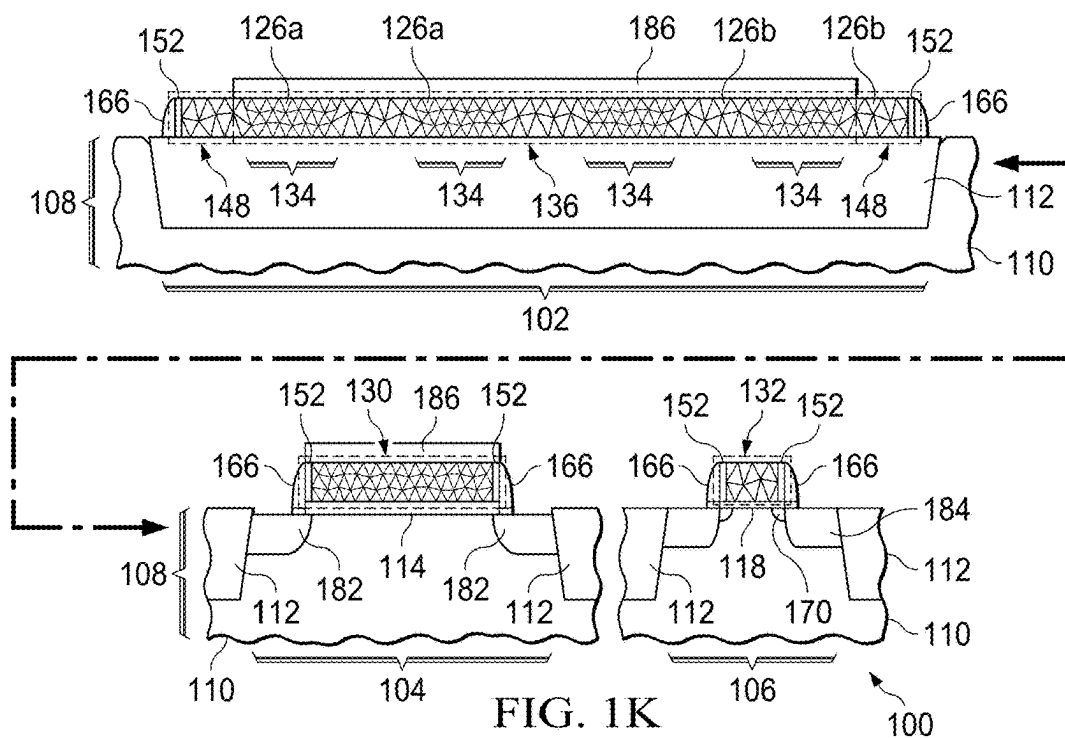


FIG. 1H







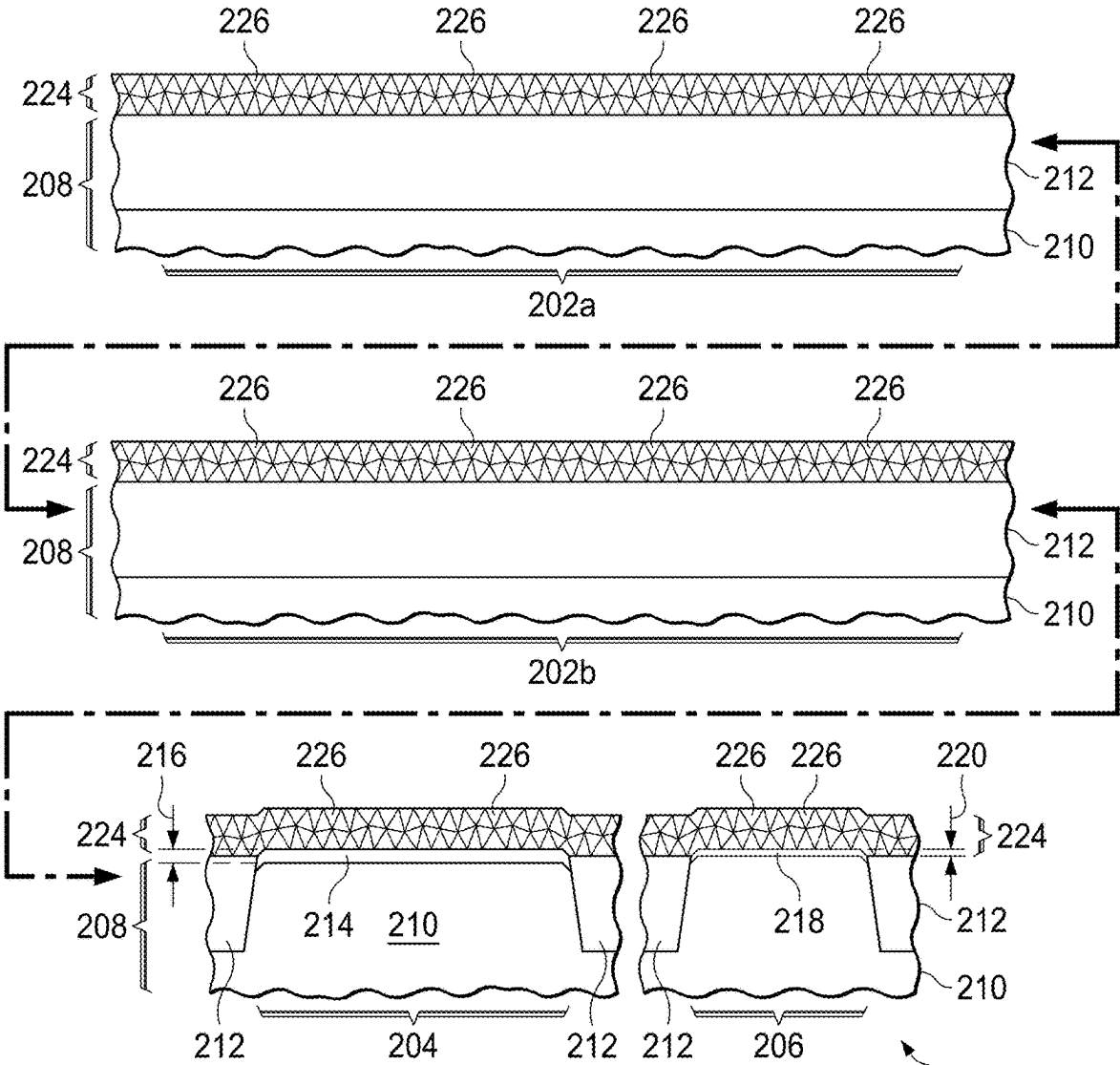


FIG. 2A

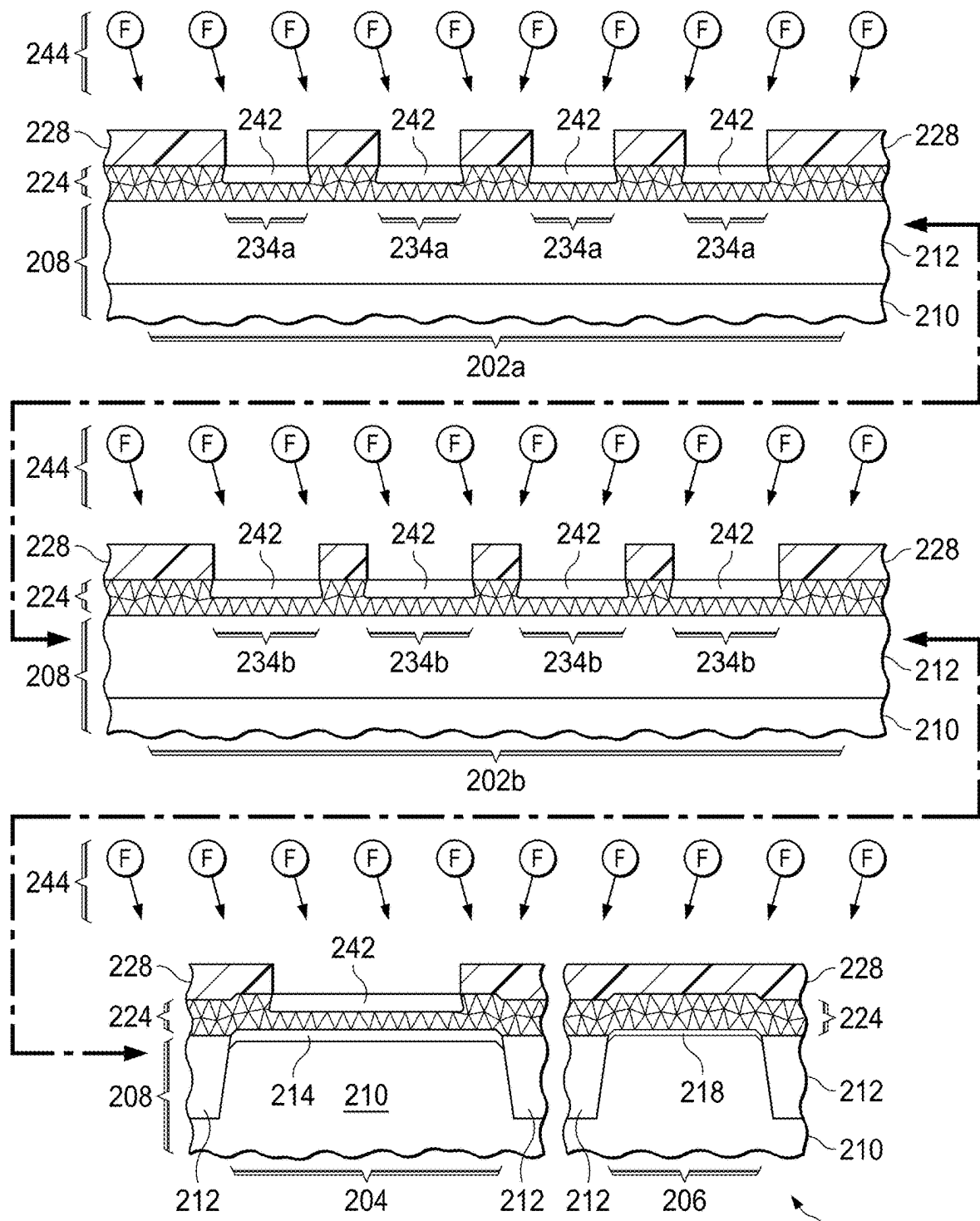
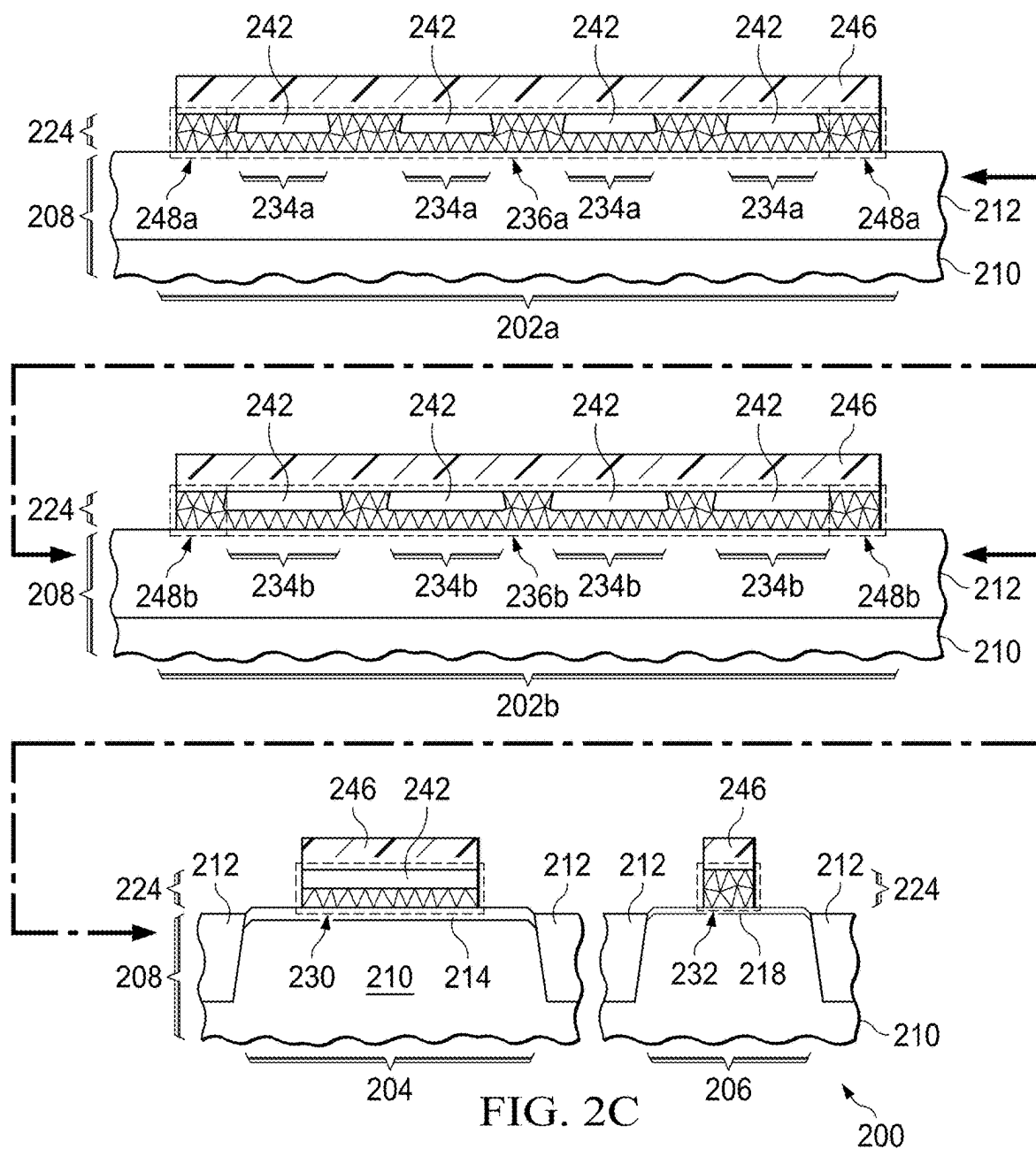
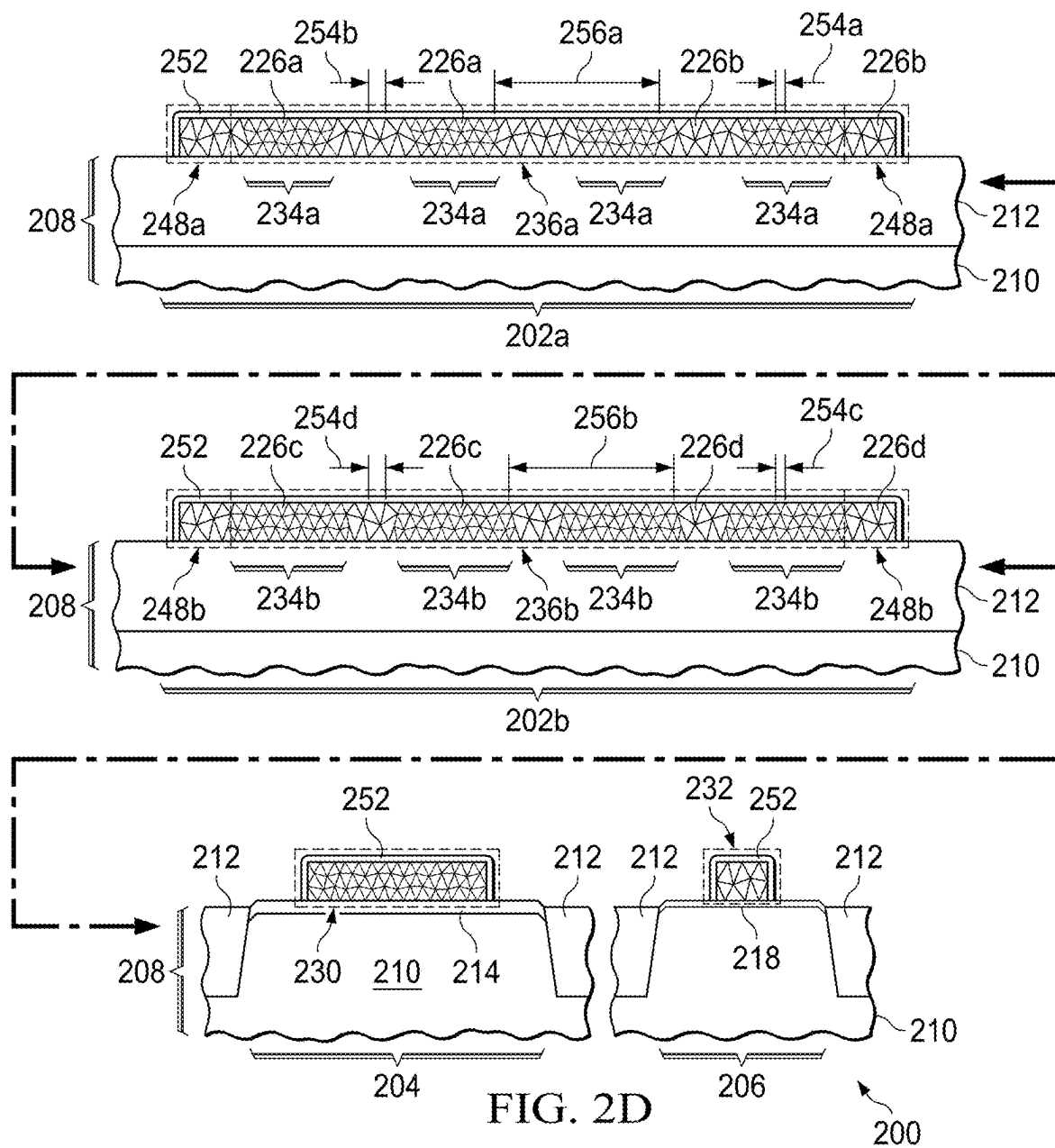
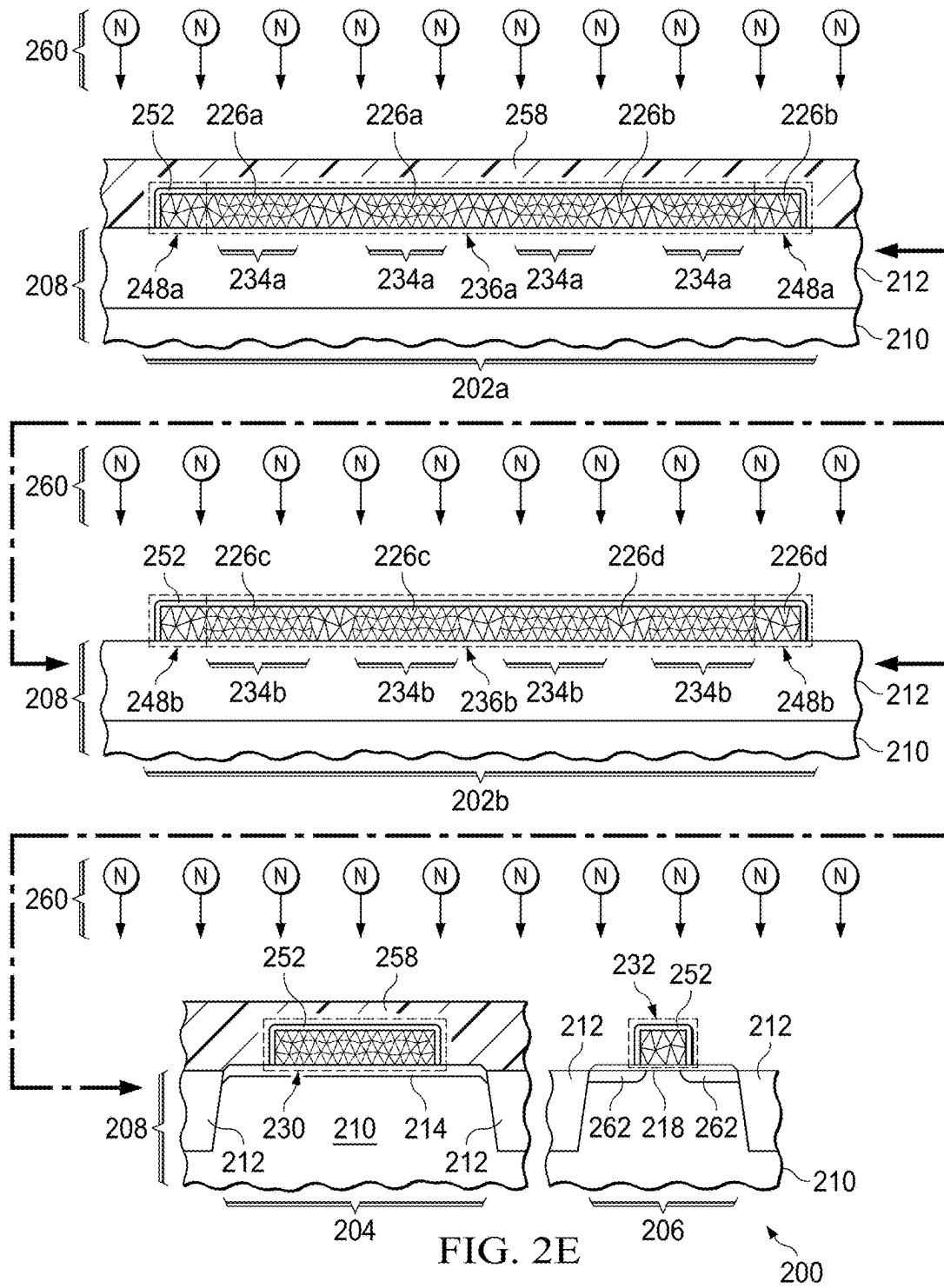


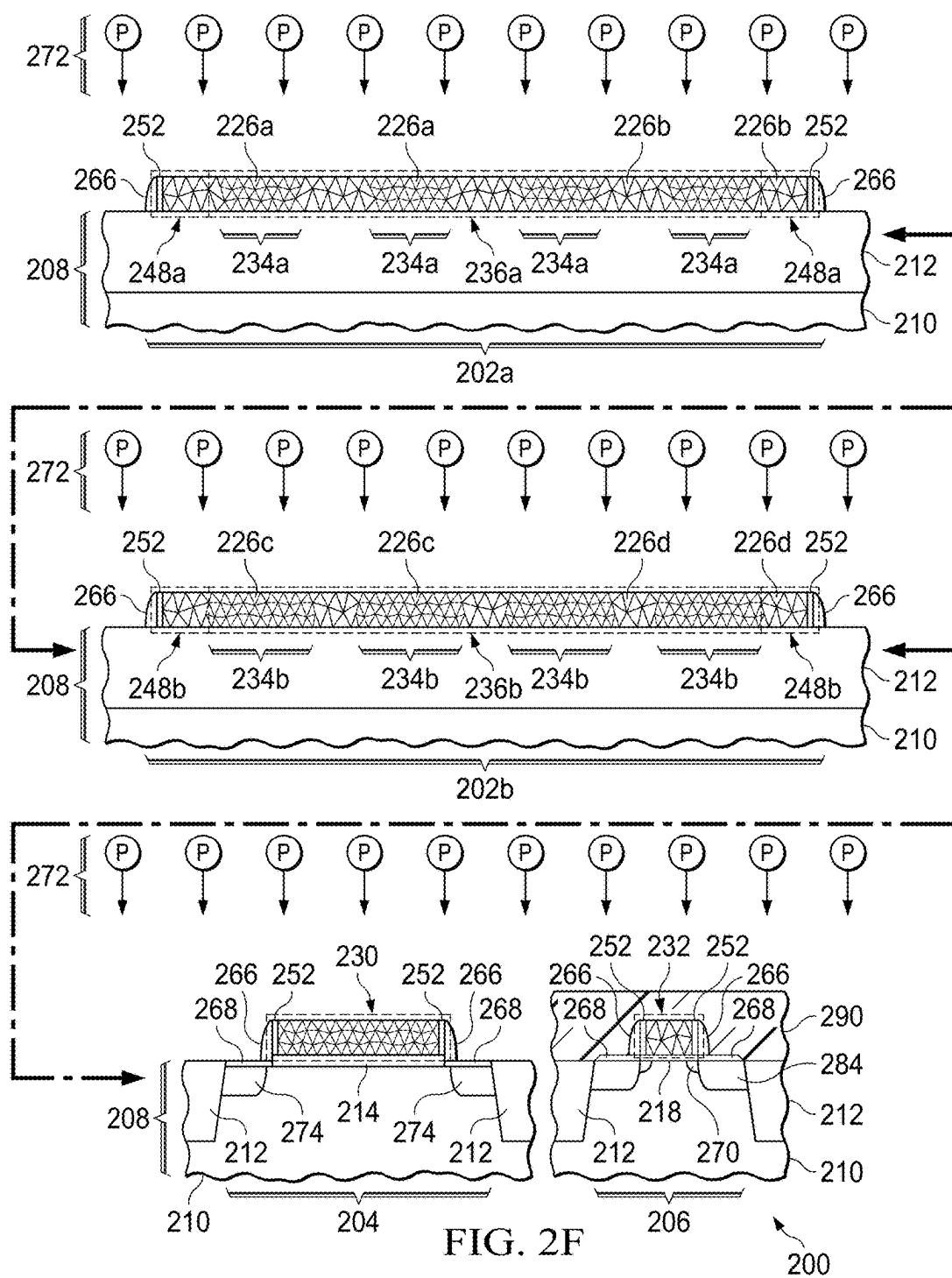
FIG. 2B

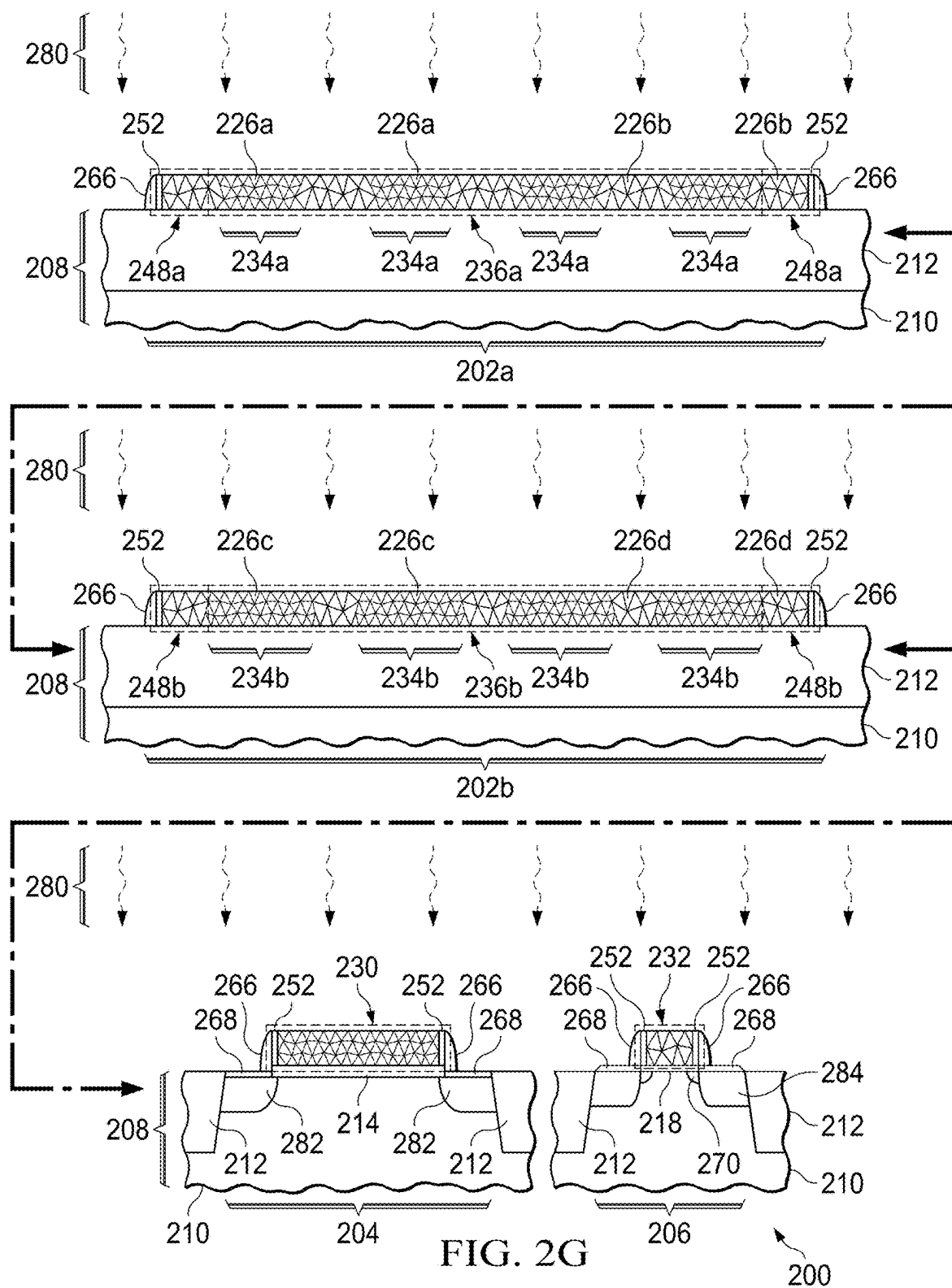
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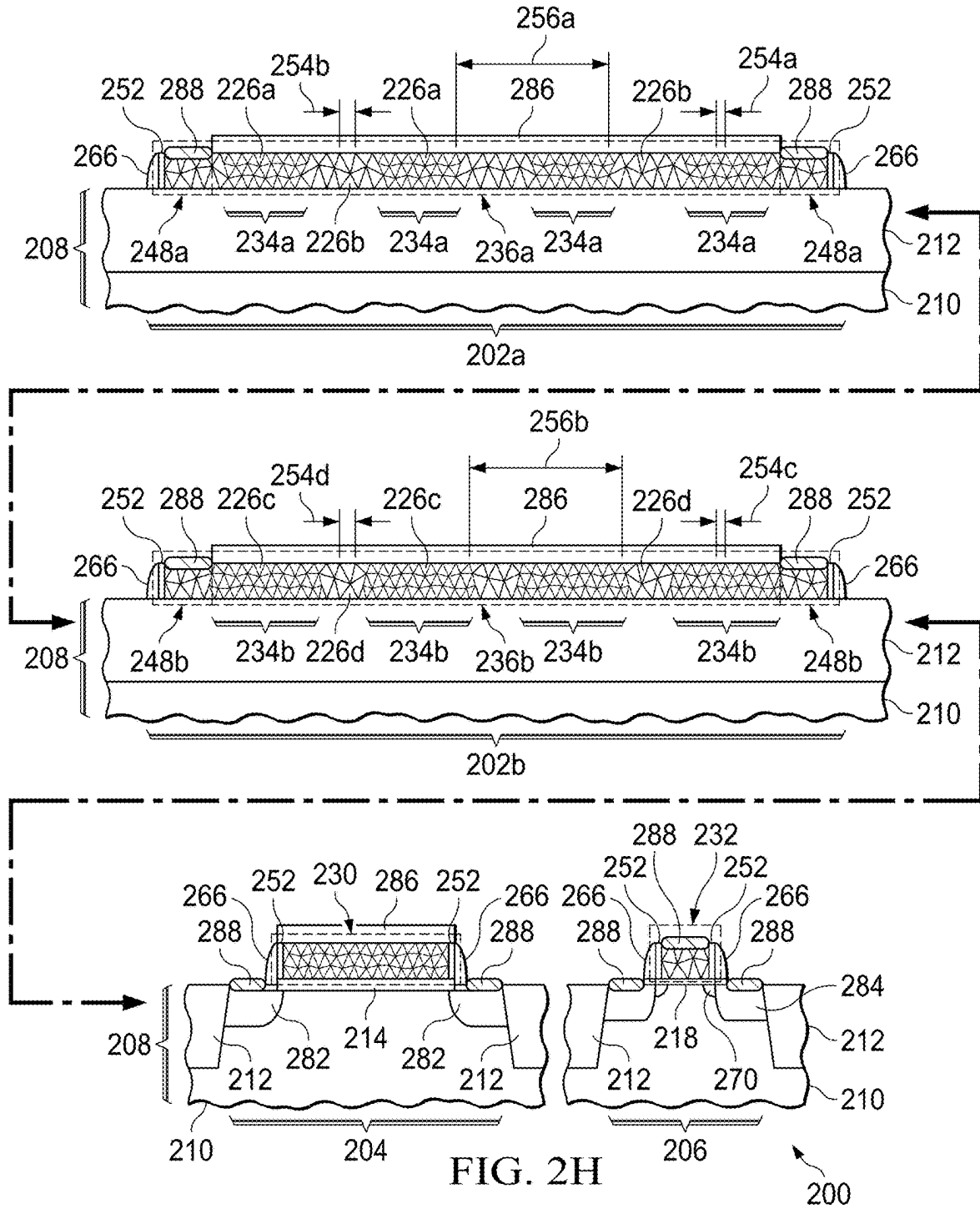












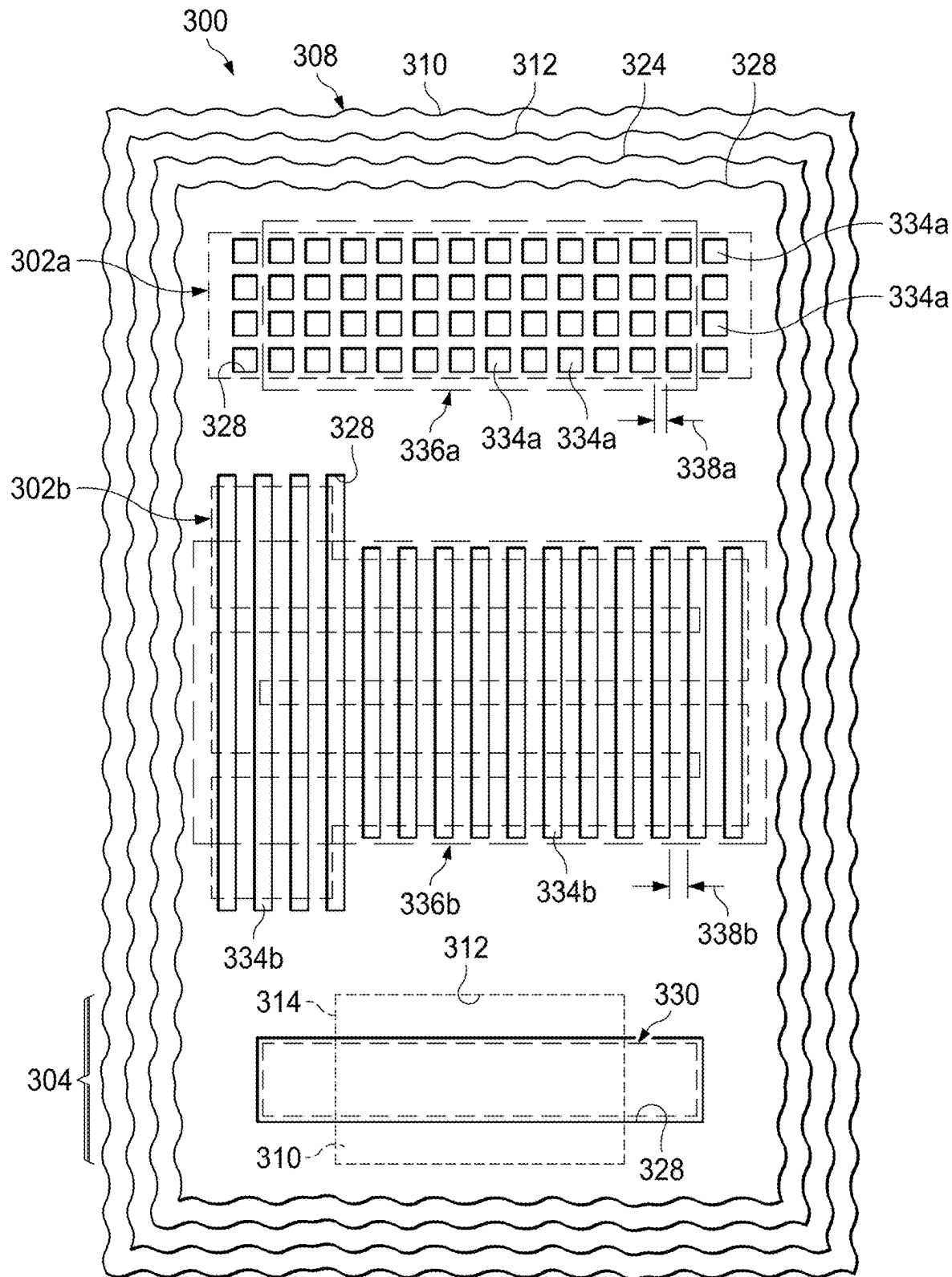


FIG. 3

SEMICONDUCTOR DEVICE WITH LOW NOISE TRANSISTOR AND LOW TEMPERATURE COEFFICIENT RESISTOR

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application is a continuation of U.S. patent application Ser. No. 18/317,227, filed on May 15, 2023, which is a continuation of U.S. patent application Ser. No. 17/086,421, filed on Nov. 1, 2020, now U.S. Pat. No. 11,676,961, the contents of which are herein incorporated by reference in their entirety.

TECHNICAL FIELD

[0002] This disclosure relates to the field of semiconductor devices. More particularly, but not exclusively, this disclosure relates to polycrystalline silicon resistors in semiconductor devices.

BACKGROUND OF THE INVENTION

[0003] Some semiconductor devices include resistors of polycrystalline silicon, commonly referred to as polysilicon. Polysilicon resistors have some advantages, such as tunable sheet resistance, attained by varying dopant concentrations in the polysilicon. Polysilicon resistors have temperature coefficients, which are relative changes in resistance as a function of temperature, that range from -200 parts per million per degree Centigrade ($\text{ppm}/^{\circ}\text{C}$.) to $+250$ $\text{ppm}/^{\circ}\text{C}$. It is sometimes desirable to attain a specific temperature coefficient in a polysilicon resistor; doing so undesirably increases process complexity and fabrication cost for the semiconductor device.

SUMMARY OF THE INVENTION

[0004] The present disclosure introduces a semiconductor device including a resistor having a resistor body including polycrystalline silicon, referred to herein as polysilicon. The resistor body includes fluorine in the polysilicon. The resistor body has a laterally alternating distribution of silicon grain sizes. The semiconductor device further includes a metal oxide semiconductor (MOS) transistor having a gate including polysilicon. The polysilicon of the gate includes fluorine with a higher average concentration than the polysilicon of the resistor body.

[0005] The semiconductor device may be formed by forming a gate/resistor layer including polysilicon over a substrate of the semiconductor device. A fluorine implant mask is formed over the gate/resistor layer, exposing the gate/resistor layer in an area for the gate and over implant segments in an area for the resistor body. The implant segments do not cover the entire area for the resistor body. Fluorine is implanted into the gate/resistor layer where exposed by the fluorine implant mask. The gate/resistor layer is patterned to form the gate and the resistor body. The semiconductor device is heated to diffuse the fluorine throughout the resistor body.

BRIEF DESCRIPTION OF THE FIGURES

[0006] FIG. 1A through FIG. 1L are cross sections of a semiconductor device including a resistor, a first MOS transistor, and a second MOS transistor, depicted in an example method of formation.

[0007] FIG. 2A through FIG. 2H are cross sections of a semiconductor device including a first resistor, a second resistor, a first MOS transistor, and a second MOS transistor, depicted in another example method of formation.

[0008] FIG. 3 is a top view of a semiconductor device including a first resistor, a second resistor, and an MOS transistor.

DETAILED DESCRIPTION

[0009] The present disclosure is described with reference to the attached figures. The figures are not drawn to scale and they are provided merely to illustrate the disclosure. Several aspects of the disclosure are described below with reference to example applications for illustration. It should be understood that numerous specific details, relationships, and methods are set forth to provide an understanding of the disclosure. The present disclosure is not limited by the illustrated ordering of acts or events, as some acts may occur in different orders and/or concurrently with other acts or events. Furthermore, not all illustrated acts or events are required to implement a methodology in accordance with the present disclosure.

[0010] In addition, although some of the embodiments illustrated herein are shown in two dimensional views with various regions having depth and width, it should be clearly understood that these regions are illustrations of only a portion of a device that is actually a three dimensional structure. Accordingly, these regions will have three dimensions, including length, width, and depth, when fabricated on an actual device. Moreover, while the present invention is illustrated by embodiments directed to active devices, it is not intended that these illustrations be a limitation on the scope or applicability of the present invention. It is not intended that the active devices of the present invention be limited to the physical structures illustrated. These structures are included to demonstrate the utility and application of the present invention to presently preferred embodiments.

[0011] A semiconductor device is formed on a substrate including a semiconductor material. The semiconductor device includes a metal oxide semiconductor (MOS) transistor and a resistor. The MOS transistor includes a gate dielectric layer formed on the semiconductor material, and a gate on the gate dielectric layer. The gate includes polycrystalline silicon, referred to herein as polysilicon. Polysilicon has grains of monocrystalline silicon, less than 10 microns in size, randomly oriented with respect to each other. Surfaces of the grains of monocrystalline silicon are referred to as grain boundaries; adjacent grains contact each other at the grain boundaries. The resistor has a resistor body including polysilicon. The polysilicon of the gate includes fluorine, and the polysilicon of the resistor body includes fluorine. The resistor body has a lower average concentration of fluorine than the gate.

[0012] A method of forming the semiconductor device includes forming a gate/resistor layer including polysilicon over the substrate of the semiconductor device. A fluorine implant mask is formed over the gate/resistor layer. The fluorine implant mask exposes the gate/resistor layer in an area for the gate of the MOS transistor, and exposes the gate/resistor layer over implant segments in an area for the resistor body. The implant segments do not cover the area for the resistor body, and the implant segments are laterally separated by portions of the gate/resistor layer covered by the fluorine implant mask, so that the fluorine implant mask

exposes a fraction of the area for the resistor body, the fraction being less than 100 percent. Fluorine is implanted into the gate/resistor layer where exposed by the fluorine implant mask. The implanted fluorine amorphizes the polysilicon in a top layer of the polysilicon where exposed by the fluorine implant mask. The gate/resistor layer is patterned to form the gate and the resistor body. The semiconductor device is heated, causing the amorphized polysilicon to recrystallize; the implanted fluorine causes the recrystallized polysilicon to have smaller grains than the polysilicon that was not implanted with the fluorine. Thus, the implant segments have smaller grains than the polysilicon between the implant segments, producing a laterally alternating distribution of silicon grain sizes in the resistor body. When the semiconductor device is heated, the fluorine diffuses in the polysilicon. In the resistor body, the fluorine diffuses from the polysilicon that was implanted with the fluorine into the polysilicon that was not implanted with the fluorine, resulting in a fluorine concentration in the polysilicon that was not implanted that is at least 95 percent of a fluorine concentration in the polysilicon that was implanted. The fluorine in the gate is also uniformly distributed.

[0013] Dopants are introduced into the resistor body and the gate to provide a desired electrical conductivity. The dopants may include p-type dopants, such as boron, and may include n-type dopants such as phosphorus and arsenic. A portion of the dopants may be distributed throughout interiors of the grains of monocrystalline silicon, generating free charge carriers such as holes, for p-type dopants, and electrons, for n-type dopants. Electrical current that flows through the interiors of the grains is similar to electrical current that flows through doped monocrystalline silicon, in that a primary component of resistance is scattering of the free charge carriers by lattice defects in the interiors of the grains. Scattering cross sections of these lattice defects increases with increasing temperature, resulting in higher resistance with increasing temperature of the polysilicon, producing a positive temperature coefficient of resistance for the electrical current that flows through the interiors of the grains.

[0014] The temperature coefficient of resistance is a change in resistance for a 1 degree Centigrade ($^{\circ}\text{C}$.) increase in temperature from an initial temperature, divided by the resistance at the initial temperature. The initial temperature is frequently set at 20°C . The temperature coefficient of resistance is frequently expressed in parts per million per degree Centigrade ($\text{ppm}/^{\circ}\text{C}$.). The temperature coefficient of resistance can be positive, in which case the resistance increases when the temperature rises, or negative, in which case the resistance decreases when the temperature rises. In an example, a resistor having a resistance of 1000 ohms at 20°C . and a temperature coefficient of resistance of $+100\text{ ppm}/^{\circ}\text{C}$., would have a change of the resistance at 25°C . of $[+100 \times 10^{-6} (1/^{\circ}\text{C}.)] \times [1000 (\text{ohms})] \times [5 (^{\circ}\text{C}.)] = +0.5\text{ ohms}$. In another example, a resistor having a resistance of 5000 ohms at 20°C . and a temperature coefficient of resistance of $-200\text{ ppm}/^{\circ}\text{C}$., would have a change of the resistance at 30°C . of $[-200 \times 10^{-6} (1/^{\circ}\text{C}.)] \times [5000 (\text{ohms})] \times [10 (^{\circ}\text{C}.)] = -10\text{ ohms}$. In a further example, a resistor having a resistance of 10000 ohms at 20°C . and a temperature coefficient of resistance of $0\text{ ppm}/^{\circ}\text{C}$., would have a change of the resistance at 30°C . of $[0 \times 10^{-6} (1/^{\circ}\text{C}.)] \times [10000 (\text{ohms})] \times [10 (^{\circ}\text{C}.)] = 0\text{ ohms}$, that is no change in the resistance.

[0015] Another portion of the dopants may be accumulated at the grain boundaries, generating heavily doped regions less than 1 micron wide. P-type heavily doped regions produce valence band wells that accumulate holes. N-type heavily doped regions produce conduction band wells that accumulate electrons. Electrical current flowing across the heavily doped regions requires thermal energy to move the free charge carriers out of the band wells. As temperature of the polysilicon increases, more thermal energy is available, so that more free charge carriers are raised out of the band wells, which reduces electrical resistance. Thus, the electrical current flowing across the heavily doped regions has a negative temperature coefficient of resistance. A temperature coefficient of resistance for the resistor body includes contributions from the positive temperature coefficient of resistance from the interiors of the grains and the negative temperature coefficient of resistance from the grain boundaries. The temperature coefficient of resistance for the resistor body depends on how much of the dopants is distributed throughout the interiors of the grains and how much of the dopants is accumulated at the grain boundaries.

[0016] The fluorine in the resistor body displaces some of the dopants from the grain boundaries into the interiors of the grains, thereby increasing the contribution of the positive temperature coefficient from the interiors of the grains and decreasing the contribution of the negative temperature coefficient from the grain boundaries. Thus, the fluorine in the resistor body increases the temperature coefficient of resistance for the resistor body. The temperature coefficient of resistance may be adjusted by adjusting an amount of fluorine in the resistor body.

[0017] In the gate, a portion of the fluorine accumulates at an interface between the polysilicon of the gate and the gate dielectric layer. The fluorine at the interface bonds with silicon and reduces noise in the MOS transistor.

[0018] It is noted that terms such as top, bottom, over, and under may be used in this disclosure. These terms should not be construed as limiting the position or orientation of a structure or element, but should be used to provide spatial relationship between structures or elements. For the purposes of this disclosure, the terms “lateral” and “laterally” refer to a direction parallel to a plane of the top surface of the semiconductor material.

[0019] FIG. 1A through FIG. 1L are cross sections of a semiconductor device 100 including a resistor 102, a first MOS transistor 104, and a second MOS transistor 106, depicted in an example method of formation. In this example, the first MOS transistor 104 is described as an n-channel first MOS transistor 104, and the second MOS transistor 106 is described as an n-channel second MOS transistor 106. In alternate versions of this example, the first MOS transistor 104 may be implemented as a p-channel first MOS transistor 104, or the second MOS transistor 106 may be implemented as a p-channel second MOS transistor 106, or both the first MOS transistor 104 and the second MOS transistor 106 may be implemented as p-channel MOS transistors 104 and 106. The semiconductor device 100 is formed on a substrate 108. The substrate 108 may be implemented as a bulk semiconductor wafer, or a silicon-on-insulator (SOI) wafer, by way of example. The substrate 108 includes a semiconductor material 110. The semiconductor material 110 may include monocrystalline silicon, and may be implemented as an upper portion of a bulk

silicon wafer, a silicon epitaxial layer, or a silicon film of an SOI wafer, for example. Field oxide **112** may be formed in the substrate **108**. The field oxide **112** may include silicon dioxide or silicon dioxide-based dielectric material. In this example, the field oxide **112** extends under the resistor **102**, and laterally isolates the first MOS transistor **104** and the second MOS transistor **106**. For the purposes of this disclosure, the term “laterally” refers to a direction parallel to a plane of a top surface of the semiconductor material **110**, that is, the surface of the semiconductor material **110** extending through the first MOS transistor **104** and the second MOS transistor **106**. The field oxide **112** may be formed by a shallow trench isolation (STI) process, which includes forming an isolation trench in the semiconductor material **110**, filling the isolation trench with the silicon dioxide or silicon dioxide-based dielectric material, and removing the silicon dioxide or silicon dioxide-based dielectric material from over the semiconductor material **110** adjacent to the isolation trench. The field oxide **112** may then have an STI configuration, which includes straight sidewalls in the semiconductor material **110**, inclined at 80 degrees to 90 degrees to the top surface of the semiconductor material **110**, and being coplanar with the top surface within 100 nanometers. FIG. 1A depicts the field oxide **112** having an STI configuration. In an alternate version of this example, the field oxide **112** may be formed by a local oxidation of silicon (LOCOS) process, which includes patterning a masking layer, such as a silicon nitride layer, to expose the semiconductor material **110** in an area for the field oxide **112**. Silicon dioxide is formed by a thermal oxidation process on the semiconductor material **110** where exposed by the masking layer, to form the field oxide **112**. The silicon dioxide extends partway under edges of the masking layer to form a tapered edge of the field oxide **112**, commonly referred to as a bird’s beak.

[0020] A first gate dielectric layer **114** is formed on the semiconductor material **110** in an area for the first MOS transistor **104**. The first gate dielectric layer **114** may include silicon dioxide, formed by a thermal oxidation process. The first gate dielectric layer **114** may include nitrogen, added by exposure to a nitrogen plasma, to improve dielectric reliability of the first gate dielectric layer **114**. The first gate dielectric layer **114** may further include one or more additional dielectric materials, such as hafnium oxide, zirconium oxide, or tantalum oxide, to increase a dielectric constant of the first gate dielectric layer **114**. Other compositions of the first gate dielectric layer **114** are within the scope of this example. In this example, the first gate dielectric layer **114** may have a first thickness **116** of 2 nanometers to 10 nanometers.

[0021] A second gate dielectric layer **118** is formed on the semiconductor material **110** in an area for the second MOS transistor **106**. The second gate dielectric layer **118** may have a composition similar to the first gate dielectric layer **114**, as a result of being formed concurrently, or may have a different composition. In this example, the second gate dielectric layer **118** may have a second thickness **120** of 2 nanometers to 10 nanometers. The second thickness **120** may be equal to the first thickness **116**, as a result of being formed concurrently, or may be less than the first thickness **116**.

[0022] In one version of this example, the first MOS transistor **104** may be implemented in an analog circuit, and the second MOS transistor **106** may be implemented in a logic circuit, with the first MOS transistor **104** operating at

a first drain-source potential that is higher than a second drain-source potential employed to operate the second MOS transistor **106**. In another version of this example, the first MOS transistor **104** may be implemented in a low-noise analog circuit, and the second MOS transistor **106** may be implemented in a high speed analog circuit, with the first MOS transistor **104** operating at a first drain-source potential that is equal to, or higher than, a second drain-source potential employed to operate the second MOS transistor **106**.

[0023] A third gate dielectric layer **122** may be formed over other areas of the semiconductor material **110**, such as areas adjacent to the area for the resistor **102**. The third gate dielectric layer **122** may be formed concurrently with either the first gate dielectric layer **114** or the second gate dielectric layer **118**, or may be formed separately.

[0024] A gate/resistor layer **124** is formed on the field oxide **112**, the first gate dielectric layer **114**, the second gate dielectric layer **118**, and the third gate dielectric layer **122**. The gate/resistor layer **124** includes polysilicon, and may include dopants, such as boron or phosphorus. The gate/resistor layer **124** may have a thickness of 50 nanometers to 1 micron, by way of example. The gate/resistor layer **124** may be formed by a chemical vapor deposition (CVD) process that includes thermal decomposition of silane or disilane at 550° C. to 650° C. and 100 millitorr to 500 millitorr pressure. Dopant gases, such as borane or phosphine, may be introduced with the silane or disilane to add dopants, boron or phosphorus, respectively, to the gate/resistor layer **124**.

[0025] The gate/resistor layer **124** includes grains **126** of monocrystalline silicon. Adjacent grains **126** contact each other at grain boundaries, which are surfaces of the grains **126**.

[0026] Referring to FIG. 1B, a fluorine implant mask **128** is formed over the gate/resistor layer **124**. The fluorine implant mask **128** may include photoresist and may be formed by a photolithographic process. The fluorine implant mask **128** may further include anti-reflection material, such as a bottom anti-reflection coat (BARC) under the photoresist. The fluorine implant mask **128** exposes the gate/resistor layer **124** in an area for a subsequently-formed first gate **130**, shown in FIG. 1E, of the first MOS transistor **104**. The fluorine implant mask **128** may expose all of the area for the first gate **130**, as indicated in FIG. 1B, to maximize an amount of fluorine in the first gate **130**. The fluorine implant mask **128** covers the gate/resistor layer **124** in an area for a subsequently-formed second gate **132**, shown in FIG. 1E, of the second MOS transistor **106**. The fluorine implant mask **128** exposes the gate/resistor layer **124** over implant segments **134** of a subsequently-formed resistor body **136**, shown in FIG. 1E, of the resistor **102**. The implant segments **134** do not completely cover the resistor body **136**; the implant segments **134** may occupy 25 percent to 75 percent of the resistor body **136**, for example. The implant segments **134** are laterally separated by portions of the gate/resistor layer **124** that are covered by the fluorine implant mask **128**. The fluorine implant mask **128** has separation widths **138** between adjacent instances of the implant segments **134**; the separation width **138** may be less than 1 micron, to advantageously enable diffusion of fluorine throughout the resistor body **136**.

[0027] In this example, an amorphizing species **140**, labeled as “A” in FIG. 1B, is implanted into the gate/resistor

layer 124 where exposed by the fluorine implant mask 128. The amorphizing species 140 may be referred to as a pre-amorphization implant (PAI) species, and the process of implanting the amorphizing species 140 may be referred to as the PAI. The amorphizing species 140 may include silicon, germanium, indium, or antimony, for example. Other amorphizing species are within the scope of this example. The amorphizing species 140 may be implanted at a total dose of $1 \times 10^{14} \text{ cm}^{-2}$ to $5 \times 10^{15} \text{ cm}^{-2}$, by way of example. The amorphizing species 140 amorphizes the polysilicon in the gate/resistor layer 124, to form amorphous silicon regions 142 in the gate/resistor layer 124 where exposed by the fluorine implant mask 128, in the implant segments 134 and in the area for the first gate 130. The amorphous silicon regions 142 may extend partway in the gate/resistor layer 124 toward the substrate 108, as depicted in FIG. 1B. Amorphizing the polysilicon in the gate/resistor layer 124 may assist diffusion of subsequently-implanted fluorine in the resistor body 136 between the implant segments 134. The amorphizing species 140 may be implanted at a tilt angle of 20 degrees to 40 degrees, to extend the amorphous silicon regions 142 under the fluorine implant mask 128 and thereby increase diffusion of subsequently-implanted fluorine in the resistor body 136 between the implant segments 134.

[0028] Referring to FIG. 1C, a first dose of fluorine 144, labeled as “F” in FIG. 1C, is implanted into the gate/resistor layer 124 where exposed by the fluorine implant mask 128. The first dose of fluorine 144 may be implanted at a first total dose to attain a desired noise level in the first MOS transistor 104. The first total dose depends on the thickness of the gate/resistor layer 124. By way of example, for a thickness of the gate/resistor layer 124 between 150 nanometers and 200 nanometers, the first total dose may be between $4 \times 10^{15} \text{ cm}^{-2}$ to $8 \times 10^{15} \text{ cm}^{-2}$. The resistor body 136 receives an effective fluorine dose of the first dose of fluorine 144 that is less than the total dose due to the portions of the fluorine implant mask 128 covering the gate/resistor layer 124 between the implant segments 134. The effective fluorine dose may be estimated as a product of the total dose and a ratio of a combined area of the implant segments 134 to the area of the resistor body 136. As an example, for a value of the total dose of $6 \times 10^{15} \text{ cm}^{-2}$ and a value of the ratio of the combined area of the implant segments 134 to the area of the resistor body 136 of 0.5, the effective fluorine dose may be estimated at $3 \times 10^{15} \text{ cm}^{-2}$. The ratio of the combined area of the implant segments 134 to the area of the resistor body 136 may be selected to attain an effective fluorine dose to provide a desired temperature coefficient of resistance in the resistor body 136. The first dose of fluorine 144 may be implanted at a tilt angle of 20 degrees to 40 degrees, to extend the implanted first dose of fluorine 144 under the fluorine implant mask 128 and thereby increase diffusion of subsequently-implanted fluorine in the resistor body 136 between the implant segments 134.

[0029] In an alternate version of this example, the amorphizing species 140 of FIG. 1B may be implanted at a lower dose, so that the amorphous silicon regions 142 are not formed until the first dose of fluorine 144 is implanted. Reducing the dose of the amorphizing species 140 may reduce a fabrication cost of the semiconductor device 100.

[0030] After the first dose of fluorine 144 is implanted into the gate/resistor layer 124, the fluorine implant mask 128 may be removed. Photoresist and other organic material in

the fluorine implant mask 128 may be removed by an asher process using oxygen radicals, followed by a wet clean process using an aqueous mixture of sulfuring acid and hydrogen peroxide, or an aqueous mixture of ammonium fluoride and hydrogen peroxide. Other methods for removing the fluorine implant mask 128 are within the scope of this example.

[0031] Referring to FIG. 1D, a gate etch mask 146 is formed over the gate/resistor layer 124, covering the area for the first gate 130, the area for the second gate 132, and the area for the resistor body 136. The first gate 130, the second gate 132, and the resistor body 136 are shown in FIG. 1E. The gate etch mask 146 may also cover areas for subsequently-formed resistor heads 148 of the resistor 102; the resistor heads 148 are shown in FIG. 1E.

[0032] The gate etch mask 146 may include hard mask material, such as silicon dioxide, or amorphous carbon, over the gate/resistor layer 124, and photoresist over the hard mask material. The photoresist may be patterned by a photolithographic process, and the hard mask material may be subsequently patterned by a dry etch process using the patterned photoresist as a mask. The gate etch mask 146 may also include anti-reflection material. The anti-reflection material may include an organic anti-reflection material, such as BARC, or may include an inorganic anti-reflection material, such as silicon nitride.

[0033] Referring to FIG. 1E, a gate etch process removes polysilicon from the gate/resistor layer 124 of FIG. 1D where exposed by the gate etch mask 146, leaving remaining gate/resistor layer 124 to form the resistor body 136 and the resistor heads 148 of the resistor 102, form the first gate 130 of the first MOS transistor 104, and form the second gate 132 of the second MOS transistor 106. The gate etch process may be implemented as a reactive ion etch (RIE) process using halogen radicals 150, labeled “H” in FIG. 1E. The halogen radicals 150 may include fluorine radicals, chlorine radicals, or bromine radicals. The halogen radicals may be supplied by any of various gas species, such as diatomic halogen gases (F_2 , Cl_2 , or Br_2), carbon tetrafluoride (CF_4), sulfur hexafluoride (SF_6), or boron trichloride (BCl_3), of hydrogen bromide (HBr). The amorphous silicon regions 142 may remain in an amorphous state during the gate etch process.

[0034] After the gate etch process is completed, the gate etch mask 146 may be removed. Photoresist organic anti-reflection material, and amorphous carbon in the gate etch mask 146 may be removed by an asher process, followed by a wet clean process. Silicon dioxide and silicon nitride in the gate etch mask 146 may be removed by a plasma etch process using fluorine radicals and carbon, with a high selectivity to the polysilicon.

[0035] Referring to FIG. 1F, a polysilicon oxide layer 152 is formed on the resistor body 136 and the resistor heads 148, the first gate 130, and the second gate 132. The polysilicon oxide layer 152 may be formed by a thermal oxidation process, which heats the semiconductor device 100 to a temperature of at least 800°C . in an oxygen-containing ambient for 20 minutes to 100 minutes, followed by an anneal process which heats the semiconductor device 100 to a temperature of at least 800°C . in an inert ambient for 20 minutes to 50 minutes. During the thermal oxidation process, the amorphous silicon in the amorphous silicon regions 142 of FIG. 1E is recrystallized into polysilicon in the implant segments 134. The first dose of fluorine 144 of

FIG. 1C in the implant segments **134** inhibits grain growth when the amorphous silicon is recrystallized, so that the grains **126a** of crystalline silicon in the implant segments **134** have a first average size **154a** that is smaller than a second average size **154b** of the grains **126b** between the implant segments **134**. Thus, the resistor body **136** has a laterally alternating distribution of the silicon grain sizes **154a** and **154b**. The alternating distribution of silicon grain sizes has a lateral pitch **156** that is defined by the fluorine implant mask **128** of FIG. 1C. The lateral pitch **156** may be less than 2 microns, to provide a more uniform distribution of the first dose of the fluorine **144** in the resistor body **136**, compared to forming the resistor body **136** with a larger lateral pitch.

[0036] In an alternate version of this example, the polysilicon oxide layer **152** may be formed by a plasma enhanced chemical vapor deposition (PECVD) process at a temperature sufficiently low that the amorphous silicon in the amorphous silicon regions **142** does not recrystallize. In this alternate version, recrystallization of the amorphous silicon occurs later in the fabrication sequence for forming the semiconductor device **100**.

[0037] Referring to FIG. 1G, a lightly doped drain (LDD) mask **158** is formed over the semiconductor device **100**, exposing the second MOS transistor **106**, and covering the resistor **102** and the first MOS transistor **104**. The LDD mask **158** may include photoresist that is patterned by a photolithographic process.

[0038] LDD dopants **160** are implanted into the semiconductor material **110** where exposed by the LDD mask **158**. In this example, the LDD dopants **160**, labeled “N” in FIG. 1G, are implemented as n-type dopants, such as primarily phosphorus and arsenic, and optionally antimony. The LDD dopants **160** may be implanted with a total dose of $1 \times 10^{15} \text{ cm}^{-2}$ to $5 \times 10^{15} \text{ cm}^{-2}$, by way of example. The LDD dopants **160** form LDD implanted regions **162** in the semiconductor material **110** adjacent to the second gate **132**. The LDD dopants **160** are blocked from the resistor **102** and the first MOS transistor **104** by the LDD mask **158**.

[0039] A second dose of fluorine **164** may optionally be implanted into the semiconductor material **110** where exposed by the LDD mask **158**. The second dose of fluorine **164** may be implanted at a total dose of 100 percent to 200 percent of the dose for the LDD dopants **160**, for example. The second dose of fluorine **164** may provide a diffusion suppressant function for the LDD dopants **160** in the LDD implanted regions **162**. In one version of this example, the LDD dopants **160** may be implanted at a tilt angle of 0 degrees to 3 degrees, to limit a lateral extent of the LDD implanted regions **162** under the second gate **132**, and the second dose of fluorine **164** may be implanted separately at a tilt angle of 15 degrees to 30 degrees to place the second dose of fluorine **164** further under the second gate **132** than the LDD dopants **160**.

[0040] Halo dopants, not shown, may be implanted into the semiconductor material **110** where exposed by the LDD mask **158**. The halo dopants have a conductivity type that is opposite from the LDD dopants **160**; in this example, in which the LDD dopants **160** are n-type dopants, the halo dopants are implemented as p-type dopants, such as boron. The halo dopants are implanted at a tilt angle of 20 degrees to 40 degrees, to place the halo dopants further under the second gate **132** than the LDD dopants **160**.

[0041] The LDD mask **158** is subsequently removed. The LDD mask **158** may be removed as disclosed in reference to removal of the fluorine implant mask **128** of FIG. 1C.

[0042] Referring to FIG. 1H, sidewall spacers **166** are formed on the polysilicon oxide layer **152** contacting lateral surfaces of the resistor **102**, the first gate **130**, and the second gate **132**. The sidewall spacers **166** may include one or more layers of dielectric material, such as silicon nitride and silicon dioxide. The sidewall spacers **166** may be formed by forming conformal layers of the silicon nitride and silicon dioxide over the semiconductor device **100** by one or more low pressure chemical vapor deposition (LPCVD) processes or PECVD processes. The silicon dioxide may be formed using dichlorosilane and nitrous oxide, or using tetraethyl orthosilicate (TEOS), formally named tetraethoxysilane. The silicon nitride may be formed using dichlorosilane and ammonia, or using bis(tertiary-butyl-amino) silane (BT-BAS). After the conformal layers are formed, the silicon nitride and silicon dioxide are removed from horizontal surfaces of the semiconductor device by an anisotropic etch process, such as an RIE process using fluorine radicals, leaving the sidewall spacers **166** in place. The sidewall spacers **166** may extend 50 nanometers to 200 nanometers laterally from the lateral surfaces of the resistor **102**, the first gate **130**, and the second gate **132**. The polysilicon oxide layer **152** may be removed from horizontal surfaces of the resistor **102**, the first gate **130**, and the second gate **132** during the anisotropic etch process, as depicted in FIG. 1H. Alternatively, a portion or all of the polysilicon oxide layer **152** may remain on the horizontal surfaces of the resistor **102**, the first gate **130**, and the second gate **132** after the sidewall spacers **166** are formed.

[0043] A protective oxide layer **168** may be formed on exposed areas of the semiconductor material **110** adjacent to the first gate **130**, and the second gate **132**. A portion of the protective oxide layer **168** may be formed by the same process used to form the polysilicon oxide layer **152**. A portion of the protective oxide layer **168** may be formed by a PECVD process.

[0044] The semiconductor device **100** may be heated in an LDD anneal process to repair lattice damage and activate the implanted LDD dopants **160** of FIG. 1G in the LDD implanted regions **162** of FIG. 1G, forming LDD regions **170** in the semiconductor material **110** adjacent to, and extending partway under, the second gate **132**. The LDD anneal process may be implemented as a rapid thermal anneal, a spike anneal, or a flash anneal, by way of example. A rapid thermal anneal may heat the semiconductor device **100** to 1000 C to 1150° C. for 5 seconds to 60 seconds, and may be implemented in a rapid thermal processor using an incandescent lamp. A spike anneal may heat the semiconductor device **100** to 1100 C to 1250° C. for 100 milliseconds to 5 seconds, and may be implemented an arc flash lamp. A flash anneal may heat an upper portion of the semiconductor device **100** containing the LDD implanted regions **162** to 1200° C. to 1350° C. for 50 microseconds to 1 millisecond, and may be implemented by a flash lamp or scanned laser.

[0045] Referring to FIG. 1I, source/drain dopants **172** are implanted into the semiconductor material **110** adjacent to the sidewall spacers **166**, and into the resistor **102**, the first gate **130**, and the second gate **132**. The source/drain dopants **172** may be blocked from the substrate **108** by a source/drain implant mask, not shown, covering other areas of the

semiconductor device **100**, such as p-channel MOS transistors. In this example, the source/drain dopants **172**, labeled “N” in FIG. 1I, are implemented as n-type dopants, such as primarily phosphorus and arsenic, and optionally antimony. The source/drain dopants **172** may be implanted with a total dose of $2 \times 10^{15} \text{ cm}^{-2}$ to $8 \times 10^{15} \text{ cm}^{-2}$, by way of example. The implanted source/drain dopants **172** increase an n-type dopant concentration in the resistor body **136** and the resistor heads **148**. By way of example, for a case in which the resistor body **136** has a thickness of 100 nanometers to 150 nanometers, the source/drain dopants **172** may provide an average concentration of n-type dopants in the resistor body **136** of $2 \times 10^{20} \text{ cm}^{-3}$ to $5 \times 10^{20} \text{ cm}^{-3}$.

[0046] The implanted source/drain dopants **172** form first source/drain implanted regions **174** in the semiconductor material **110** adjacent to the sidewall spacers **166** on the first gate **130**. The implanted source/drain dopants **172** also form second source/drain implanted regions **176** in the semiconductor material **110** adjacent to the sidewall spacers **166** on the second gate **132**.

[0047] An optional third dose of fluorine **178** may be implanted into the semiconductor material **110** adjacent to the sidewall spacers **166**, and into the resistor **102**, the first gate **130**, and the second gate **132**. The third dose of fluorine **178** is less than the effective fluorine dose of the first dose of fluorine **144** disclosed in reference to FIG. 1C. For example, the third dose of fluorine **178** may be 10 percent to 20 percent of the first dose of fluorine **144**.

[0048] In this example, the resistor body **136** may retain the laterally alternating distribution of the silicon grain sizes **154a** and **154b** while the source/drain dopants **172** and the third dose of fluorine **178** are implanted, as indicated in FIG. 1I, because the doses of the source/drain dopants **172** and the third dose of fluorine **178** are insufficient to amorphize the polysilicon in the resistor body **136**.

[0049] Referring to FIG. 1J, the semiconductor device **100** is heated in a source/drain anneal process **180** to repair lattice damage and activate the implanted source/drain dopants **172** in the first source/drain implanted regions **174** and the second source/drain implanted regions **176** of FIG. 1I. The source/drain anneal process **180** forms first source/drain regions **182** in the semiconductor material **110** adjacent to, and extending under, the sidewall spacers **166** on the first gate **130**. The source/drain anneal process **180** forms second source/drain regions **184** in the semiconductor material **110** adjacent to, and extending partway under, the sidewall spacers **166** on the second gate **132**. The second source/drain regions **184** are merged with the LDD regions **170**. The source/drain anneal process **180** may be implemented as a rapid thermal anneal, a spike anneal, or a flash anneal, by way of example.

[0050] Referring to FIG. 1K, a silicide blocking layer **186** is formed on the semiconductor device **100**, covering the resistor body **136** and at least a portion of the first gate **130**. The silicide blocking layer **186** exposes the resistor heads **148**, the first source/drain regions **182** and the second source/drain regions **184**. The silicide blocking layer **186** optionally expose the second gate **132**, as depicted in FIG. 1K. The silicide blocking layer **186** may include silicon dioxide or silicon nitride, for example. The silicide blocking layer **186** may be formed by forming a layer of dielectric material containing silicon dioxide or silicon nitride over the semiconductor device **100** by a PECVD process, to avoid high temperatures that would cause unwanted diffusion of

dopants in the semiconductor material **110**. The layer of dielectric material is patterned by forming an etch mask, not shown, over the layer of dielectric material by a photolithographic process, and removing the layer of dielectric material where exposed by the etch mask. The etch mask is subsequently removed, leaving unetched portions of the layer of dielectric material in place to provide the silicide blocking layer **186**.

[0051] The protective oxide layer **168** of FIG. 1J is removed where exposed by the sidewall spacers **166**, exposing the first source/drain regions **182** and the second source/drain regions **184**. The protective oxide layer **168** may be removed before the silicide blocking layer **186** is formed, during formation of the silicide blocking layer **186**, or after the silicide blocking layer **186** is formed.

[0052] Referring to FIG. 1L, metal silicide **188** is formed on the resistor heads **148**, the first source/drain regions **182** and the second source/drain regions **184**, and optionally on the second gate **132**. The metal silicide **188** may include titanium silicide, cobalt silicide, or nickel silicide, by way of example. The metal silicide **188** may be formed by forming a layer of metal, such as titanium, cobalt, or nickel, on the semiconductor device **100**, contacting the resistor heads **148**, the first source/drain regions **182**, the second source/drain regions **184**, and the second gate **132**. Subsequently, the semiconductor material **110** and the layer of metal are heated to react the layer of metal with silicon in the resistor heads **148**, the first source/drain regions **182**, the second source/drain regions **184**, and the second gate **132**, forming the metal silicide **188**. Unreacted metal is removed from the semiconductor device **100**, leaving the metal silicide **188** in place. The unreacted metal may be removed by a wet etch process using an aqueous mixture of sulfuric acid and hydrogen peroxide, or an aqueous mixture of nitric acid and hydrochloric acid, by way of example.

[0053] The resistor body **136** may have an average concentration of fluorine that is 40 percent to 80 percent of an average concentration of fluorine in the first gate **130**, as a result of the implant segments **134** occupying 25 percent to 75 percent of the resistor body **136**, and the third dose of fluorine **178**, of FIG. 1I, being 10 percent to 20 percent of the first dose of fluorine **144**, of FIG. 1C. In an alternate version of this example, in which the resistor body **136** is not implanted with the third dose of fluorine **178**, the resistor body **136** may have an average concentration of fluorine that is 25 percent to 75 percent of an average concentration of fluorine in the first gate **130**, as a result of the implant segments **134** occupying 25 percent to 75 percent of the resistor body **136**. Considering both versions, the resistor body **136** may have an average concentration of fluorine of $1 \times 10^{20} \text{ cm}^{-3}$ to $6.5 \times 10^{20} \text{ cm}^{-3}$.

[0054] The resistor body **136** may retain the laterally alternating distribution of the silicon grain sizes **154a** and **154b** after the metal silicide **188** is formed. Having the lateral pitch **156** of the alternating distribution at less than 2 microns may provide a uniform distribution of the fluorine in the resistor body **136**, which may advantageously provide tighter control of the temperature coefficient of resistance of the resistor body **136**, compared to a similar resistor body having a greater lateral pitch.

[0055] In one version of this example, the resistor body **136** may have a temperature coefficient of resistance that is substantially zero, within fabrication tolerances of polysilicon deposition processes and ion implantation processes

used in forming the resistor body **136**, that is, a temperature coefficient of resistance of $-20 \text{ ppm}/^\circ \text{C}$. to $20 \text{ ppm}/^\circ \text{C}$. Having the temperature coefficient of resistance that is substantially zero may advantageously provide temperature independence for a circuit containing the resistor **102**.

[0056] In another version of this example, the resistor body **136** may have a temperature coefficient of resistance in a range of a desired positive value, such as $75 \text{ ppm}/^\circ \text{C}$. to $125 \text{ ppm}/^\circ \text{C}$., for use in a sensor circuit.

[0057] The first MOS transistor **104** may advantageously have lower noise than a comparable MOS transistor having LDD regions and without fluorine in the gate. The first MOS transistor **104** may be used in a low noise analog circuit, such as an amplifier circuit, for example. The second MOS transistor **106** may advantageously have higher speed than a comparable MOS transistor without LDD regions. The second MOS transistor **106** may be used in a high speed, noise tolerant circuit such as a logic circuit.

[0058] Forming the first gate **130** with a higher average concentration of fluorine than the resistor body **136**, and attaining a desired temperature coefficient of resistance, using a common fluorine implant and a single fluorine implant mask, as disclosed in reference to FIG. 1A through FIG. 1L, may advantageously reduce a fabrication cost and complexity of the semiconductor device **100**, compared to using separate fluorine implants and two fluorine implant masks.

[0059] FIG. 2A through FIG. 2H are cross sections of a semiconductor device **200** including a first resistor **202a**, a second resistor **202b**, a first MOS transistor **204**, and a second MOS transistor **206**, depicted in another example method of formation. In this example, the first MOS transistor **204** is described as a p-channel first MOS transistor **204**, and the second MOS transistor **206** is described as an n-channel second MOS transistor **206**. In alternate versions of this example, the first MOS transistor **204** may be implemented as an n-channel first MOS transistor **204**, or the second MOS transistor **206** may be implemented as a p-channel second MOS transistor **206**. The semiconductor device **200** is formed on a substrate **208**, as disclosed in reference to FIG. 1A. The substrate **208** includes a semiconductor material **210**, which may include monocrystalline silicon, as disclosed in reference to FIG. 1A. Field oxide **212** may be formed in the substrate **208**. In this example, the field oxide **212** extends under the first resistor **202a** under the second resistor **202b**, and laterally isolates the first MOS transistor **204** and the second MOS transistor **206**. The field oxide **212** may have an STI configuration, as indicated in FIG. 2A, or may have a LOCOS configuration.

[0060] A first gate dielectric layer **214** is formed on the semiconductor material **210** in an area for the first MOS transistor **204**. In this example, the first gate dielectric layer **214** may have a first thickness **216** of 2 nanometers to 10 nanometers. A second gate dielectric layer **218** is formed on the semiconductor material **210** in an area for the second MOS transistor **206**. In this example, the second gate dielectric layer **218** may have a second thickness **220** of 2 nanometers to 10 nanometers. The second thickness **220** may be equal to the first thickness **216**, or may be less than the first thickness **216**. In one version of this example, the first MOS transistor **204** may be implemented in an analog circuit, and the second MOS transistor **206** may be implemented in a logic circuit, with the first MOS transistor **204** operating at a first drain-source potential that is higher than

a second drain-source potential employed to operate the second MOS transistor **206**. In another version of this example, the first MOS transistor **204** may be implemented in a low-noise analog circuit, and the second MOS transistor **206** may be implemented in a high speed analog circuit, with the first MOS transistor **204** operating at a first drain-source potential that is equal to, or higher than, a second drain-source potential employed to operate the second MOS transistor **206**.

[0061] A gate/resistor layer **224** is formed on the field oxide **212**, the first gate dielectric layer **214**, and the second gate dielectric layer **218**. The gate/resistor layer **224** includes polysilicon, and may include dopants, such as boron or phosphorus. The gate/resistor layer **224** may have a thickness of 50 nanometers to 1 micron, by way of example. The gate/resistor layer **224** may be formed as disclosed in reference to FIG. 1A. The gate/resistor layer **224** includes grains **226** of monocrystalline silicon. Adjacent grains **226** contact each other at grain boundaries, which are surfaces of the grains **226**.

[0062] Referring to FIG. 2B, a fluorine implant mask **228** is formed over the gate/resistor layer **224**. The fluorine implant mask **228** exposes the gate/resistor layer **224** in an area for a subsequently-formed first gate **230**, shown in FIG. 2C, of the first MOS transistor **204**. In this example, the fluorine implant mask **228** may expose all of the area for the subsequently-formed first gate **230**, to maximize an amount of fluorine in the subsequently-formed first gate **230**. The fluorine implant mask **228** covers the gate/resistor layer **224** in an area for a subsequently-formed second gate **232**, shown in FIG. 2C, of the second MOS transistor **206**. The fluorine implant mask **228** exposes the gate/resistor layer **224** over first implant segments **234a** of a subsequently-formed first resistor body **236a**, shown in FIG. 2C, of the first resistor **202a**, and exposes the gate/resistor layer **224** over second implant segments **234b** of a subsequently-formed second resistor body **236b**, shown in FIG. 2C, of the second resistor **202b**. The first implant segments **234a** occupy a first fraction of the first resistor body **236a**, and the second implant segments **234b** occupy a second fraction of the second resistor body **236b**. In this example, the second fraction is larger than the first fraction, that is, the first implant segments **234a** occupy a smaller fraction of the first resistor body **236a**, than the second implant segments **234b** occupy of the second resistor body **236b**. The first implant segments **234a** may occupy 25 percent to 50 percent of the first resistor body **236a**, and the second implant segments **234b** may occupy 50 percent to 75 percent of the second resistor body **236b**, for example. The first implant segments **234a** are laterally separated by portions of the gate/resistor layer **224** that are covered by the fluorine implant mask **228**, and similarly for the second implant segments **234b**. The fluorine implant mask **228** may have a composition and structure as disclosed in reference to FIG. 1B.

[0063] Fluorine **244**, labeled as "F" in FIG. 2B, is implanted into the gate/resistor layer **224** where exposed by the fluorine implant mask **228**. The fluorine **244** may be implanted at a total fluorine dose to attain a desired noise level in the first MOS transistor **204**. The total fluorine dose depends on the thickness of the gate/resistor layer **224**, as disclosed in reference to FIG. 1C. The first resistor body **236a** receives a first effective fluorine dose of the fluorine **244** that may be estimated as a product of the total fluorine dose and a ratio of a combined area of the first implant

segments **234a** to the area of the first resistor body **236a**. Similarly, the second resistor body **236b** receives a second effective fluorine dose of the fluorine **244** that may be estimated as a product of the total fluorine dose and a ratio of a combined area of the second implant segments **234b** to the area of the second resistor body **236b**.

[0064] In this example, the fluorine **244** may form amorphous silicon regions **242** in the gate/resistor layer **224** where exposed by the fluorine implant mask **228**, in the first implant segments **234a**, the second implant segments **234b**, and in the area for the first gate **230**. The amorphous silicon regions **242** of this example may have less than completely amorphous silicon, and so may also include small regions of crystalline silicon.

[0065] The ratio of the combined area of the first implant segments **234a** to the area of the first resistor body **236a** may be selected to attain a first effective fluorine dose to provide a desired first temperature coefficient of resistance in the first resistor body **236a**. Similarly, the ratio of the combined area of the second implant segments **234b** to the area of the second resistor body **236b** may be selected to attain a second effective fluorine dose to provide a desired second temperature coefficient of resistance in the second resistor body **236b**. The second temperature coefficient of resistance may be different from the first temperature coefficient of resistance.

[0066] In one version of this example, the first resistor body **236a** may have the first temperature coefficient of resistance substantially zero, and the first resistor **202a** may be used in a temperature-independent circuit, while the second resistor body **236b** may have the second temperature coefficient of resistance greater than zero, and the second resistor **202b** may be used in a temperature sensor circuit. In another version of this example, the first resistor body **236a** may have the first temperature coefficient of resistance less than zero, and the first resistor **202a** may be used in a sensor compensating circuit, while the second resistor body **236b** may have the second temperature coefficient of resistance substantially zero, and the second resistor **202b** may be used in a temperature-independent circuit. In a further version of this example, the first resistor body **236a** may have the first temperature coefficient of resistance less than zero, while the second resistor body **236b** may have the second temperature coefficient of resistance greater than zero, and the first resistor **202a** and the second resistor **202b** may be used together in a temperature-compensating circuit. Other combinations of temperature coefficients of resistance for the resistor bodies **236a** and **236b**, and other applications for the resistors **202a** and **202b**, are within the scope of this example.

[0067] The fluorine **244** may be implanted at a tilt angle of 20 degrees to 40 degrees, to extend the implanted fluorine **244** under the fluorine implant mask **228** and thereby increase diffusion of subsequently-implanted fluorine in the first resistor body **236a** between the first implant segments **234a** and in the second resistor body **236b** between the second implant segments **234b**.

[0068] After the fluorine **244** is implanted into the gate/resistor layer **224**, the fluorine implant mask **228** may be removed. The fluorine implant mask **228** may be removed as disclosed in reference to FIG. 1C.

[0069] Referring to FIG. 2C, a gate etch mask **246** is formed over the gate/resistor layer **224**, covering the area for the first gate **230**, the area for the second gate **232**, the area

for the first resistor body **236a**, and the area for the second resistor body **236b**. The gate etch mask **246** may also cover areas for first resistor heads **248a** of the first resistor **202a** and areas for second resistor heads **248b** of the second resistor **202b**. The gate etch mask **246** may have a composition and structure as disclosed in reference to FIG. 1D.

[0070] A gate etch process removes polysilicon from the gate/resistor layer **224** of FIG. 1D where exposed by the gate etch mask **246**, leaving remaining gate/resistor layer **224** to form the first resistor body **236a** and the first resistor heads **248a** of the first resistor **202a**, form the second resistor body **236b** and the second resistor heads **248b** of the second resistor **202b**, form the first gate **230** of the first MOS transistor **204**, and form the second gate **232** of the second MOS transistor **206**. The gate etch process may be implemented as disclosed in reference to FIG. 1E the amorphous silicon regions **242** may remain in an amorphous state during the gate etch process.

[0071] After the gate etch process is completed, the gate etch mask **246** may be removed, for example as disclosed in reference to FIG. 1E, leaving the first resistor body **236a** and the first resistor heads **248a**, the second resistor body **236b** and the second resistor heads **248b**, the first gate **230** of the first MOS transistor **204**, and the second gate **232** in place.

[0072] Referring to FIG. 2D, a polysilicon oxide layer **252** is formed on the first resistor body **236a** and the first resistor heads **248a**, on the second resistor body **236b** and the second resistor heads **248b**, on the first gate **230**, and on the second gate **232**. The polysilicon oxide layer **252** may be formed by a thermal oxidation process, or an LPCVD or PECVD process. In versions of this example in which the polysilicon oxide layer **252** is formed by the thermal oxidation process, the amorphous silicon in the amorphous silicon regions **242** of FIG. 2C is recrystallized into polysilicon in the first implant segments **234a** and the second implant segments **234b**. The fluorine **244** of FIG. 2B in the first implant segments **234a** and the second implant segments **234b** inhibits grain growth when the amorphous silicon is recrystallized. The grains **226a** of crystalline silicon in the first implant segments **234a** have a first average size **254a** that is smaller than a second average size **254b** of the grains **226b** between the first implant segments **234a**. Thus, the first resistor body **236a** has a first laterally alternating distribution of the silicon grain sizes **254a** and **254b**. The first alternating distribution of silicon grain sizes has a first lateral pitch **256a** that is defined by the fluorine implant mask **228** of FIG. 2B. The first lateral pitch **256a** may be less than 2 microns, accruing the advantage of uniform distribution of the fluorine **244**, as disclosed in reference to FIG. 1F.

[0073] Similarly, the grains **226c** of crystalline silicon in the second implant segments **234b** have a third average size **254c** that is smaller than a fourth average size **254d** of the grains **226d** between the second implant segments **234b**. Thus, the second resistor body **236b** has a second laterally alternating distribution of the silicon grain sizes **254c** and **254d**. The second alternating distribution of silicon grain sizes has a second lateral pitch **256b** that is defined by the fluorine implant mask **228**. The second lateral pitch **256b** may be less than 2 microns, to provide a more uniform distribution of the fluorine **244** in the second resistor body **236b**.

[0074] In versions of this example in which the polysilicon oxide layer **252** is formed by a low temperature process,

recrystallization of the amorphous silicon occurs later in the fabrication sequence for forming the semiconductor device 200. Recrystallization of the amorphous silicon may occur at an LDD anneal, for example.

[0075] Referring to FIG. 2E, an LDD mask 258 is formed over the semiconductor device 200, exposing the second resistor 202b and the second MOS transistor 206, and covering the first resistor 202a and the first MOS transistor 204. The LDD mask 258 may include photoresist that is patterned by a photolithographic process.

[0076] LDD dopants 260 are implanted into the semiconductor material 210 and the polysilicon of the second resistor 202b, where exposed by the LDD mask 258. In this example, the LDD dopants 260, labeled “N” in FIG. 2E, are implemented as n-type dopants, such as primarily phosphorus, arsenic, and antimony. The LDD dopants 260 may be implanted with a total dose of $1 \times 10^{15} \text{ cm}^{-2}$ to $5 \times 10^{15} \text{ cm}^{-2}$, by way of example. The LDD dopants 260 form LDD implanted regions 262 in the semiconductor material 210 adjacent to the second gate 232. The LDD dopants 260 are blocked from the first resistor 202a and the first MOS transistor 204 by the LDD mask 258. In a version of the example in which the second resistor body 236b has a thickness of 100 nanometers to 150 nanometers, the LDD dopants 260 may provide an average concentration of n-type dopants in the second resistor body 236b of $1 \times 10^{20} \text{ cm}^{-3}$ to $3 \times 10^{20} \text{ cm}^{-3}$.

[0077] Halo dopants, not shown, may be implanted into the semiconductor material 210 at a tilt angle of 20 degrees to 40 degrees, where exposed by the LDD mask 258. The halo dopants have a conductivity type that is opposite from the LDD dopants 260; in this example, in which the LDD dopants 260 are n-type dopants, the halo dopants are implemented as p-type dopants, such as boron.

[0078] The LDD mask 258 is subsequently removed. The LDD mask 258 may be removed as disclosed in reference to removal of the fluorine implant mask 228 of FIG. 2B.

[0079] Referring to FIG. 2F, the semiconductor device 200 may be heated in an LDD anneal process to repair lattice damage and activate the implanted LDD dopants 260 of FIG. 2E in the LDD implanted regions 262 of FIG. 2E, forming LDD regions 270 in the semiconductor material 210 adjacent to, and extending partway under, the second gate 232. The LDD anneal process may be implemented as a rapid thermal anneal, a spike anneal, or a flash anneal, by way of example. The LDD regions 270 of this example are n-type.

[0080] Second source/drain regions 284 are formed in the semiconductor material 210 adjacent to, and extending partway under, the sidewall spacers 266 on the second gate 232. The second source/drain regions 284 of this example are n-type. The second source/drain regions 284 may be formed by implanting n-type dopants, such as phosphorus, arsenic, and antimony, into the semiconductor material 210 adjacent to the sidewall spacers 266 on the second gate 232, and annealing the semiconductor material 210 to activate the implanted n-type dopants. The second source/drain regions 284 are merged with the LDD regions 270.

[0081] Sidewall spacers 266 are formed on the polysilicon oxide layer 252 contacting lateral surfaces of the first resistor 202a, the second resistor 202b, the first gate 230, and the second gate 232. The sidewall spacers 266 may have a structure and composition, and may be formed, as disclosed in reference to FIG. 1H. A protective oxide layer 268

may be formed on exposed areas of the semiconductor material 210 adjacent to the first gate 230, and the second gate 232.

[0082] A source/drain mask 290 is formed over the semiconductor device 200, exposing the first resistor 202a, the second resistor 202b, and the first MOS transistor 204, and covering the second MOS transistor 206. The source/drain mask 290 may include photoresist that is patterned by a photolithographic process.

[0083] Source/drain dopants 272 are implanted into the first gate 230, into the semiconductor material 210 adjacent to the sidewall spacers 266 on the first gate 230, into the first resistor 202a, and into the second resistor 202b. The source/drain dopants 272 are blocked from the second MOS transistor 206 by the source/drain mask 290. In this example, the source/drain dopants 272, labeled “P” in FIG. 2F, are implemented as p-type dopants, such as primarily boron, and optionally indium or gallium. The source/drain dopants 272 may be implanted with a total dose of $2 \times 10^{15} \text{ cm}^{-2}$ to $8 \times 10^{15} \text{ cm}^{-2}$, by way of example. The implanted source/drain dopants 272 provide p-type conductivity in the first resistor body 236a and the first resistor heads 248a. The implanted source/drain dopants 272 counterdope the implanted LDD dopants 260 of FIG. 2E in the second resistor body 236b and the second resistor heads 248b, and so provide p-type conductivity in the second resistor body 236b and the second resistor heads 248b. The implanted source/drain dopants 272 form first source/drain implanted regions 274 in the semiconductor material 210 adjacent to the sidewall spacers 266 on the first gate 230.

[0084] In this example, the first resistor body 236a may retain the laterally alternating distribution of the silicon grain sizes 254a and 254b, and the second resistor body 236b may retain the laterally alternating distribution of the silicon grain sizes 254c and 254d, while the source/drain dopants 272 are implanted, as indicated in FIG. 2F, because the dose of the source/drain dopants 272 is insufficient to amorphize the polysilicon in the first resistor body 236a and the second resistor body 236b.

[0085] Referring to FIG. 2G, the semiconductor device 200 is heated in a source/drain anneal process 280 to repair lattice damage and activate the implanted source/drain dopants 272 in the first source/drain implanted regions 274 of FIG. 2F, forming first source/drain regions 282 in the semiconductor material 210 adjacent to, and extending under, the sidewall spacers 266 on the first gate 230. The source/drain anneal process 280 may be implemented as a rapid thermal anneal, a spike anneal, or a flash anneal, by way of example.

[0086] Referring to FIG. 2H, a silicide blocking layer 286 is formed on the semiconductor device 200, covering the first resistor body 236a, the second resistor body 236b, and at least a portion of the first gate 230. The silicide blocking layer 286 exposes the first resistor heads 248a, the second resistor heads 248b, the first source/drain regions 282 and the second source/drain regions 284. The silicide blocking layer 286 optionally expose the second gate 232, as depicted in FIG. 2H. The silicide blocking layer 286 may have a composition, and may be formed, as disclosed in reference to FIG. 1K. The protective oxide layer 268 of FIG. 2G is removed where exposed by the sidewall spacers 266, exposing the first source/drain regions 282 and the second source/drain regions 284.

[0087] Metal silicide 288 is formed on the first resistor heads 248a, the second resistor heads 248b, the first source/drain regions 282 and the second source/drain regions 284, and optionally on the second gate 232. The metal silicide 288 may include titanium silicide, cobalt silicide, or nickel silicide, by way of example. The metal silicide 288 may be formed as disclosed in reference to FIG. 1L.

[0088] The first resistor body 236a may retain the laterally alternating distribution of the silicon grain sizes 254a and 254b after the metal silicide 288 is formed. Similarly, the second resistor body 236b may retain the laterally alternating distribution of the silicon grain sizes 254c and 254d after the metal silicide 288 is formed. Having the lateral pitches 256a and 256b of the alternating distribution at less than 2 microns may provide a uniform distribution of the fluorine in the resistor bodies 236a and 236b, which may accrue the advantage disclosed in reference to FIG. 1L.

[0089] Forming the first gate 230 with a higher average concentration of fluorine than the first resistor body 236a and with a higher average concentration of fluorine than the second resistor body 236b, and attaining temperature coefficients of resistance in the first resistor body 236a and the second resistor body 236b, using a common fluorine implant and a single fluorine implant mask, as disclosed in reference to FIG. 2A through FIG. 2H, may advantageously reduce a fabrication cost and complexity of the semiconductor device 200, compared to using separate fluorine implants and three fluorine implant masks.

[0090] FIG. 3 is a top view of a semiconductor device 300 including a first resistor 302a, a second resistor 302b, and an MOS transistor 304. The semiconductor device 300 is formed on a substrate 308, as disclosed in reference to FIG. 1A. The substrate 308 includes a semiconductor material 310, which may include monocrystalline silicon, as disclosed in reference to FIG. 1A. Field oxide 312 may be formed in the substrate 308. In this example, the field oxide 312 extends under the first resistor 302a and under the second resistor 302b. The field oxide 312 laterally surrounds a portion of the semiconductor material 310 in an area for the MOS transistor 304. A first gate dielectric layer 314 is formed on the semiconductor material 310 where exposed by the field oxide 312 in the area for the MOS transistor 304. A gate/resistor layer 324 is formed on the field oxide 312 and the first gate dielectric layer 314. The gate/resistor layer 324 includes polysilicon, and may include dopants.

[0091] A fluorine implant mask 328 is formed over the gate/resistor layer 324. The fluorine implant mask 328 exposes the gate/resistor layer 324 in an area for a subsequently-formed gate 330 of the MOS transistor 304. In this example, the fluorine implant mask 328 may expose all of the area for the subsequently-formed gate 330, as depicted in FIG. 3.

[0092] The fluorine implant mask 328 exposes the gate/resistor layer 324 over first implant segments 334a of a subsequently-formed first resistor body 336a of the first resistor 302a. The first implant segments 334a may be arranged in a two dimensional array of rectangles or squares, as depicted in FIG. 3. The first implant segments 334a occupy a first fraction of the first resistor body 336a. The fluorine implant mask 328 has first separation widths 338a between adjacent instances of the first implant segments 334a; the first separation widths 338a may be less than 1 micron.

[0093] The fluorine implant mask 328 exposes the gate/resistor layer 324 over second implant segments 334b of a subsequently-formed second resistor body 336b of the second resistor 302b. The second implant segments 334b may be arranged in a linear array of strips, as depicted in FIG. 3. The second implant segments 334b occupy a second fraction of the second resistor body 336b. The fluorine implant mask 328 has second separation widths 338b between adjacent instances of the second implant segments 334b; the second separation widths 338b may be less than 1 micron.

[0094] Formation of the semiconductor device 300 may be continued as disclosed in reference to FIG. 1B through FIG. 1L, or FIG. 2B through FIG. 2H. Formation of the semiconductor device 300 may be continued using a combination of steps as disclosed in reference to both FIG. 1B through FIG. 1L, and FIG. 2B through FIG. 2H.

[0095] Various features of the examples disclosed herein may be combined in other manifestations of example semiconductor devices. For example, the resistor 102 may be formed without the PAI 140. In another example, the resistor 102 may be formed by implanting the resistor body 136 with the LDD dopants 160 and the second dose of fluorine 164, in addition to the source/drain dopants 172. In a further example, the semiconductor device 100 may further include a p-channel MOS transistor formed with p-type LDD dopants, and the resistor 102 may be formed by implanting the resistor body 136 with the p-type LDD dopants, similar to the method disclosed in reference to FIG. 2E.

[0096] In another example, the first resistor 202a and the second resistor 202b may be formed using a PAI, similar to the PAI 140 disclosed in reference to FIG. 1B. In a further example, the semiconductor device 200 may further include a p-channel MOS transistor formed with p-type LDD dopants, and either the first resistor 202a or the second resistor 202b, or both, may be formed by implanting the first resistor body 236a or the second resistor body 236b, respectively, with the p-type LDD dopants, similar to the method disclosed in reference to FIG. 1I.

[0097] While various embodiments of the present disclosure have been described above, it should be understood that they have been presented by way of example only and not limitation. Numerous changes to the disclosed embodiments can be made in accordance with the disclosure herein without departing from the spirit or scope of the disclosure. Thus, the breadth and scope of the present invention should not be limited by any of the above described embodiments. Rather, the scope of the disclosure should be defined in accordance with the following claims and their equivalents.

What is claimed is:

1. A semiconductor device, comprising:

- a first metal oxide semiconductor (MOS) transistor including:
 - a first gate dielectric layer on a semiconductor substrate; and
 - a first gate on the first gate dielectric layer, the first gate having polysilicon with a first grain size; and
- a second metal oxide semiconductor (MOS) transistor including:
 - a second gate dielectric layer; and
 - a second gate on the second gate dielectric layer, the second gate having polysilicon with a second grain size different than the first grain size.

2. The semiconductor device of claim 1, wherein the second grain size is greater than the first grain size.

3. The semiconductor device of claim 1, wherein:
the first gate includes a first average concentration of fluorine; and
the second gate includes a second average concentration of fluorine less than the first average concentration of fluorine.
4. The semiconductor device of claim 1, wherein:
the first gate includes fluorine; and
the second gate is exclusive of fluorine.
5. The semiconductor device of claim 1, wherein the first gate dielectric layer is same as the second gate dielectric layer.
6. The semiconductor device of claim 1, further comprising:
a resistor over the semiconductor substrate, the resistor including a resistor body having polysilicon with the first grain size and the second grain size.
7. The semiconductor device of claim 6, wherein the first grain size and the second grain size of the resistor body laterally alternate.

8. The semiconductor device of claim 6, wherein the resistor body includes germanium, indium, antimony, or a combination thereof.

9. The semiconductor device of claim 6, wherein the resistor body includes n-type dopants, such as phosphorus, arsenic, antimony, or a combination thereof.

10. The semiconductor device of claim 6, wherein the resistor body includes p-type dopants, such as boron, indium, gallium, or a combination thereof.

11. The semiconductor device of claim 6, wherein the resistor is a first resistor having a first temperature coefficients of resistance, and the semiconductor device further comprises:

a second resistor having a second temperature coefficients of resistance different than the first temperature coefficients of resistance.

12. The semiconductor device of claim 1, wherein at least one of the first gate of the first MOS transistor and the second gate of the second MOS transistor includes germanium, indium, antimony, or a combination thereof.

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