US 20240284808A1

(19) **United States**

(12) **Patent Application Publication**

Chen et al.

(10) **Pub. No.: US 2024/0284808 A1**

(43) **Pub. Date: Aug. 22, 2024**

(54) **PHASE-CHANGE MATERIAL (PCM) RADIO FREQUENCY (RF) SWITCHING DEVICE WITH NOVEL SPREADER DESIGN**

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(21) Appl. No.: **18/171,380**

(22) Filed: **Feb. 20, 2023**

Publication Classification

(51) **Int. Cl.**

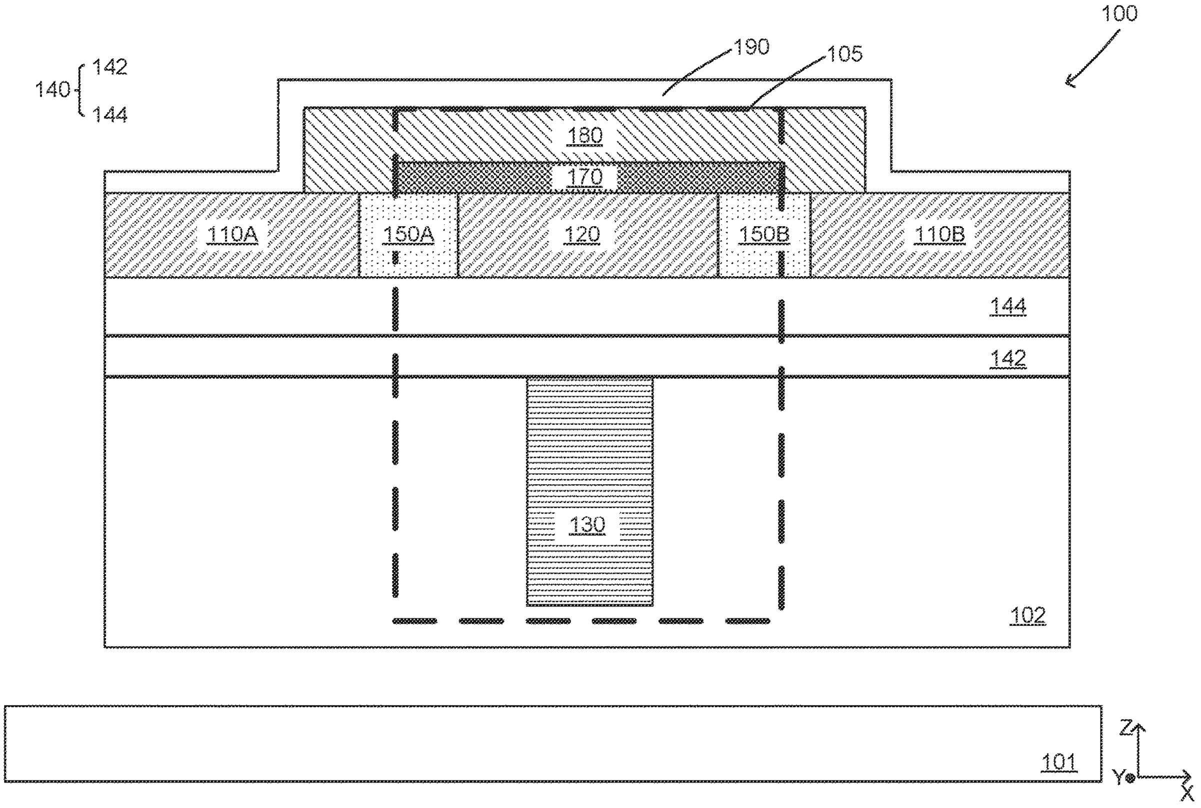
H10N 70/20	(2006.01)
H10N 70/00	(2006.01)

(52) **U.S. Cl.**

CPC ***H10N 70/231*** (2023.02); ***H10N 70/023*** (2023.02); ***H10N 70/026*** (2023.02); ***H10N 70/063*** (2023.02); ***H10N 70/066*** (2023.02); ***H10N 70/8613*** (2023.02)

(57) **ABSTRACT**

A phase-change material (PCM) switching device includes: a base dielectric layer; a spreader element disposed in the base dielectric layer, wherein the spreader element extends in a first horizontal direction and comprises: a central portion extending in the first horizontal direction and having a first width in a second horizontal direction perpendicular to the first horizontal direction; a first end portion at a first end of the central portion and having a second width in the second horizontal direction; and a second end portion at a second end of the central portion and having a third width in the second horizontal direction, and wherein at least one of the second width and the third width is larger than the first width; a heater element disposed over the spreader element; a thermal barrier element disposed on the heater element; and a PCM layer disposed on the thermal barrier element.



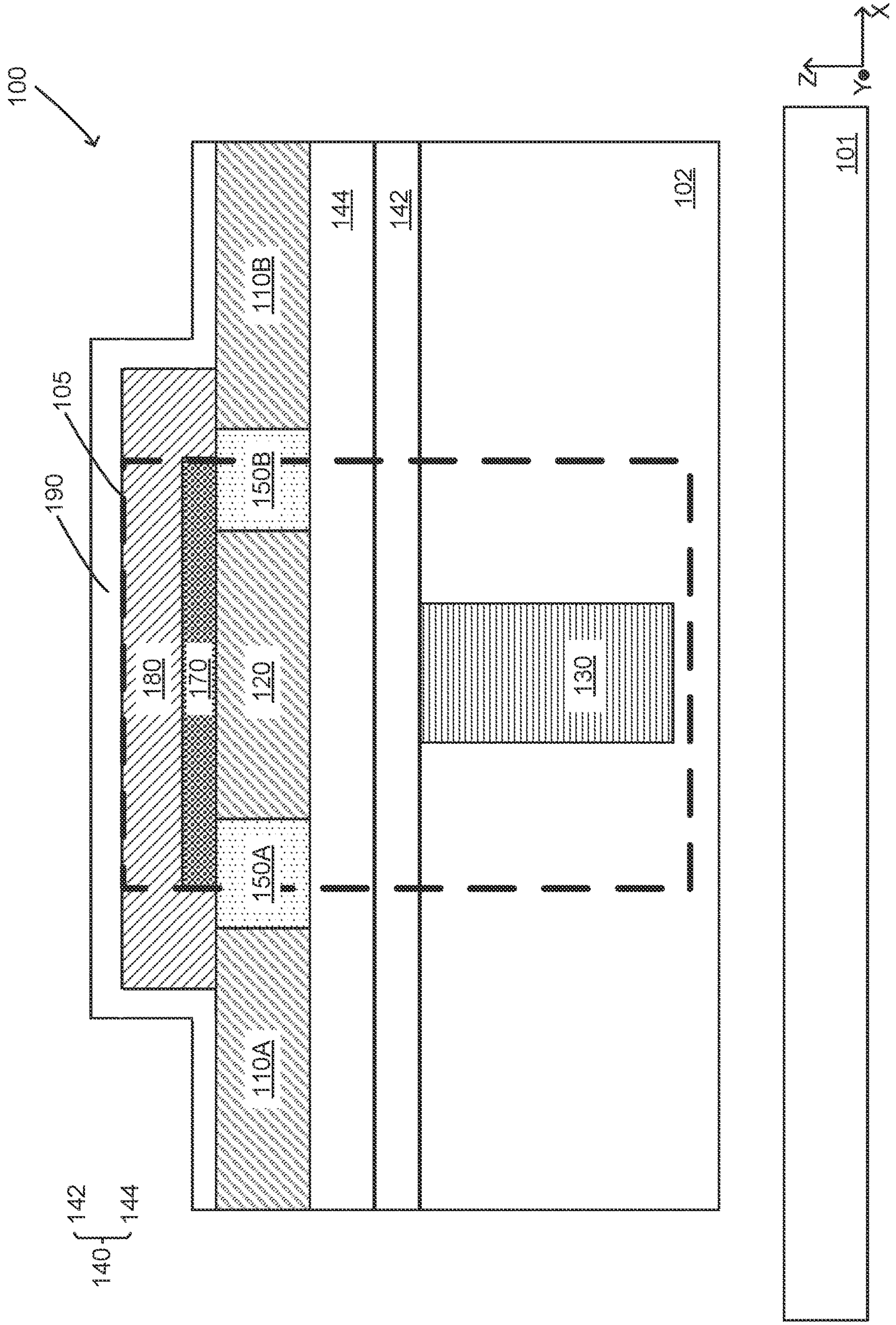

100
105
190
180
170
120
150A
150B
110A
110B
144
142
102
130
101
140
142
144
Z
Y
X

FIG. 1A

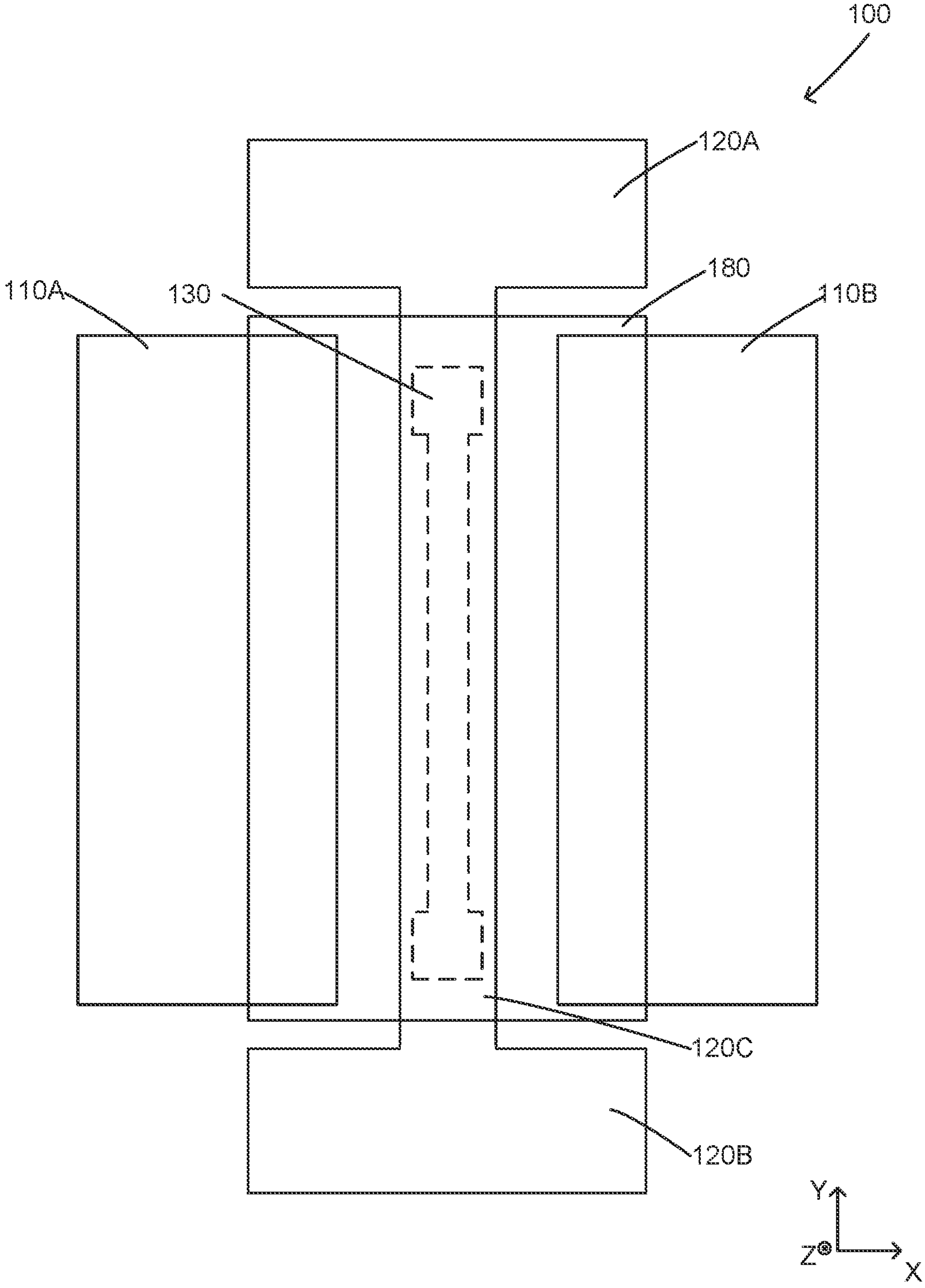


FIG. 1B

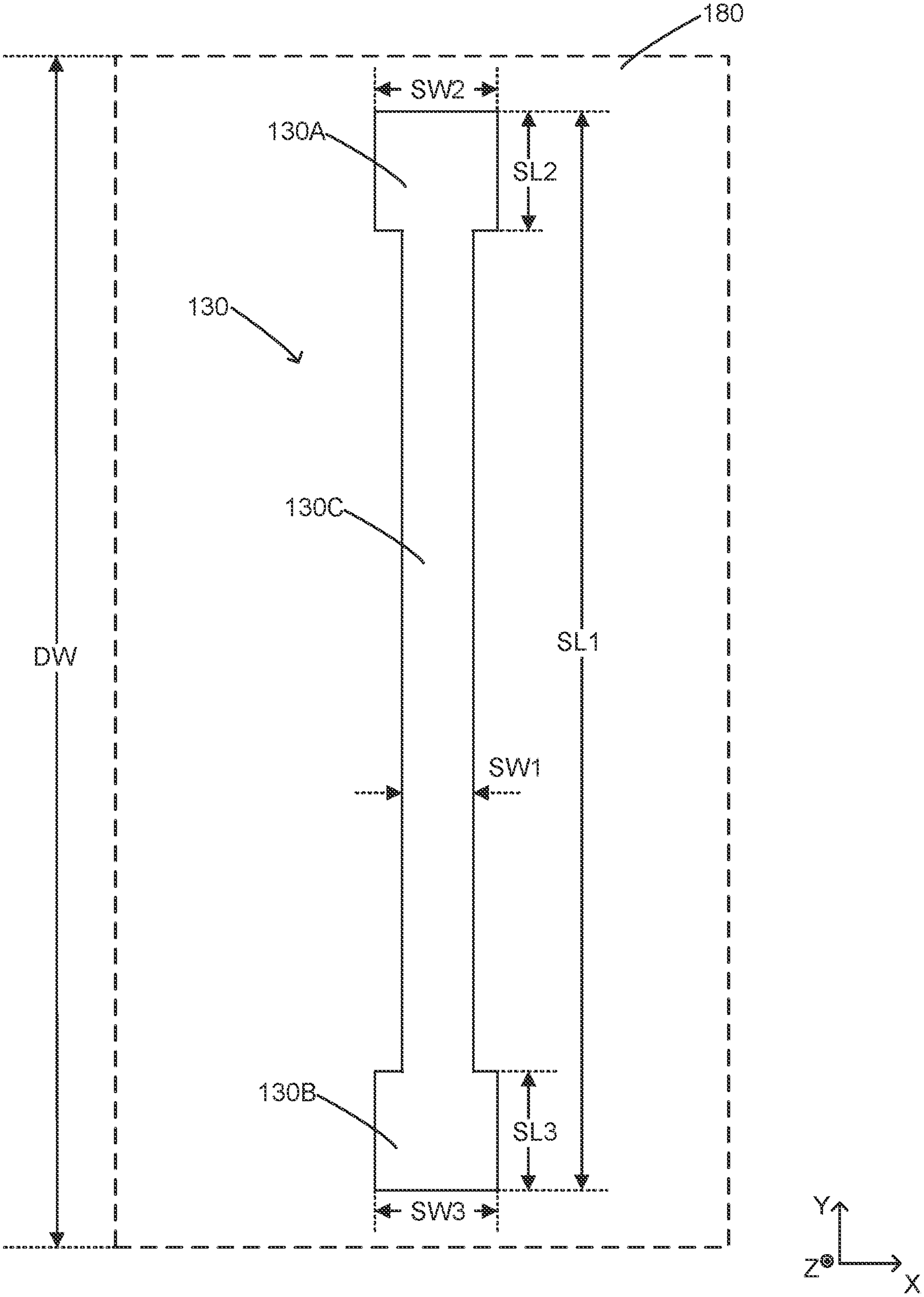


FIG. 1C

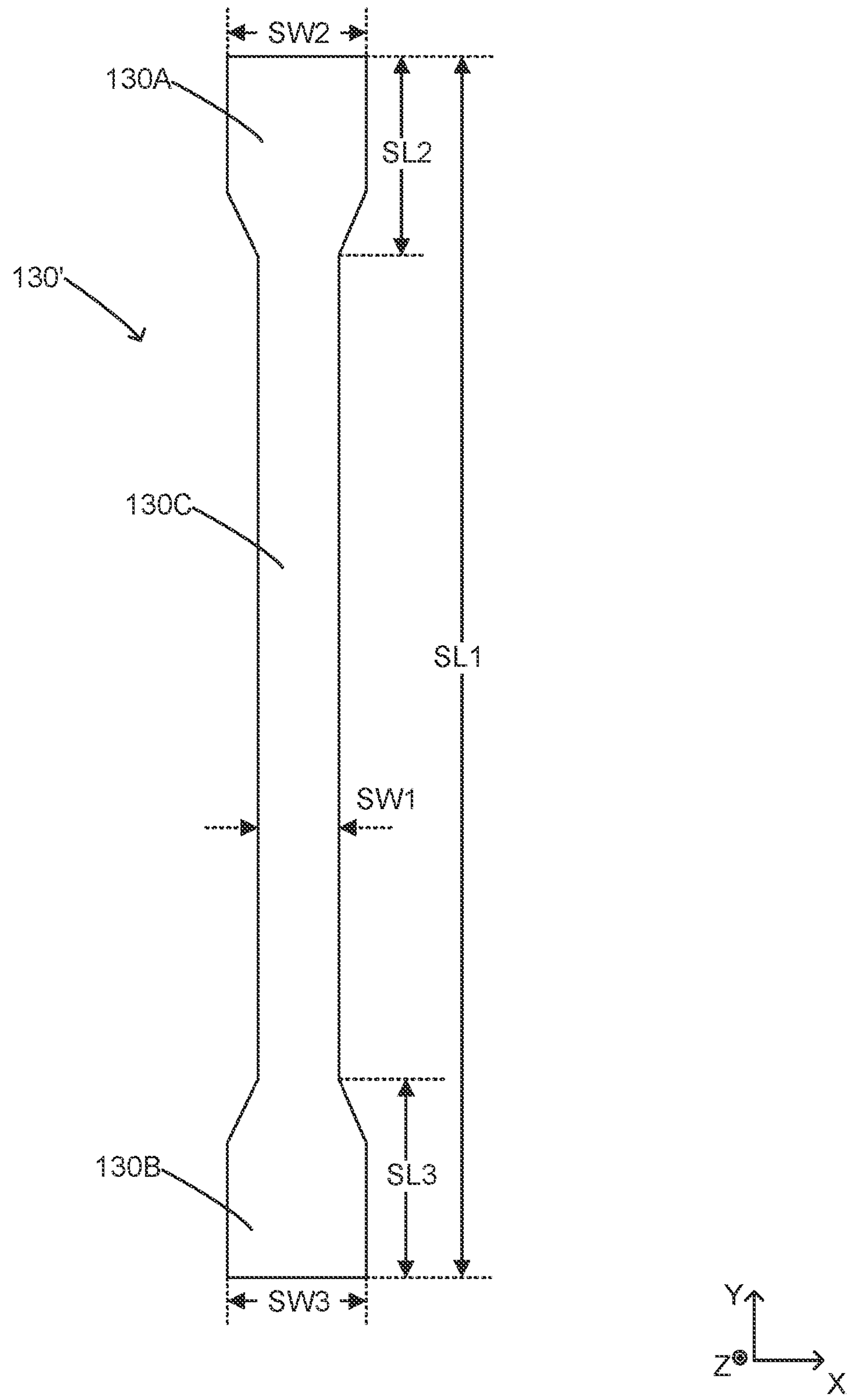


FIG. 1D

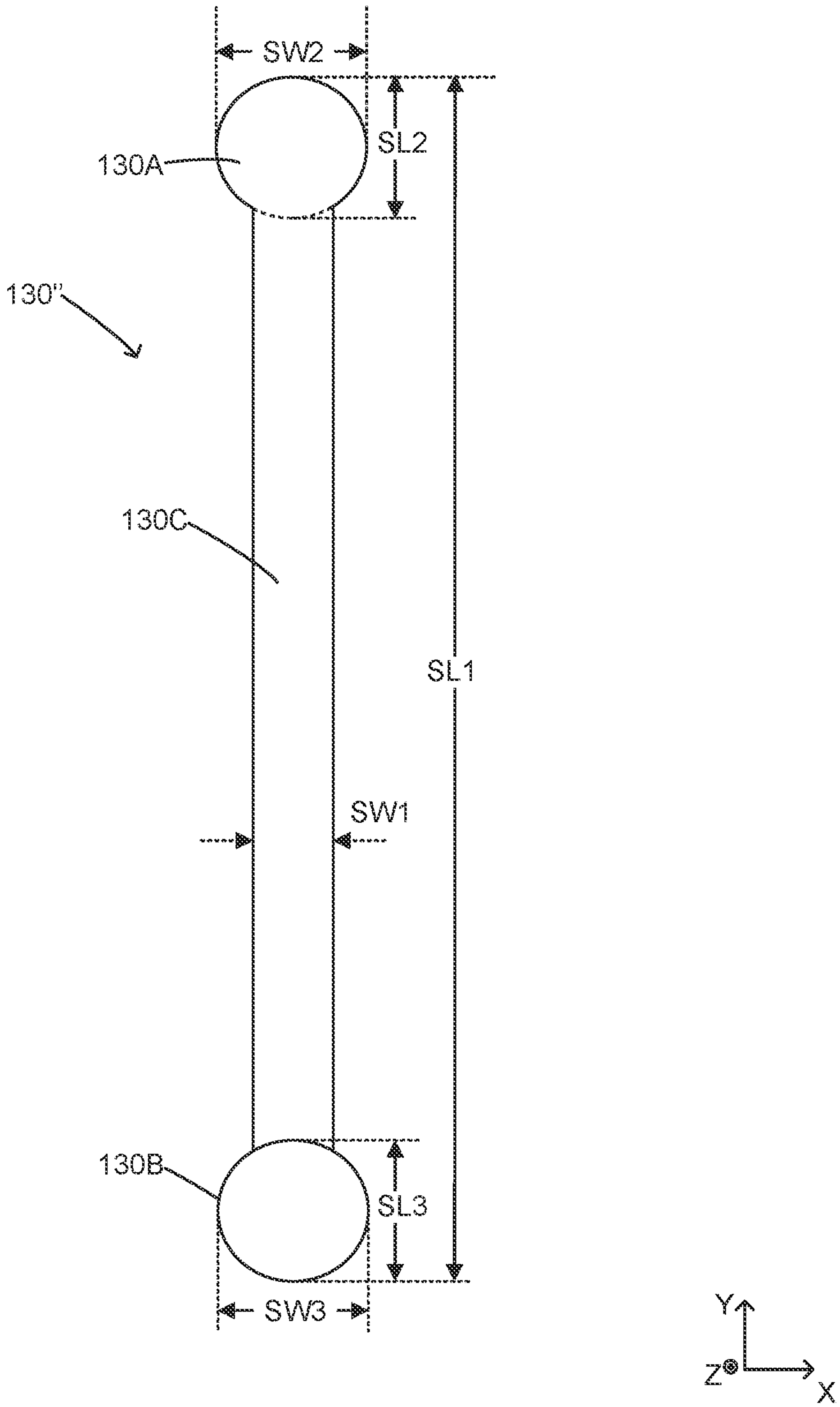


FIG. 1E

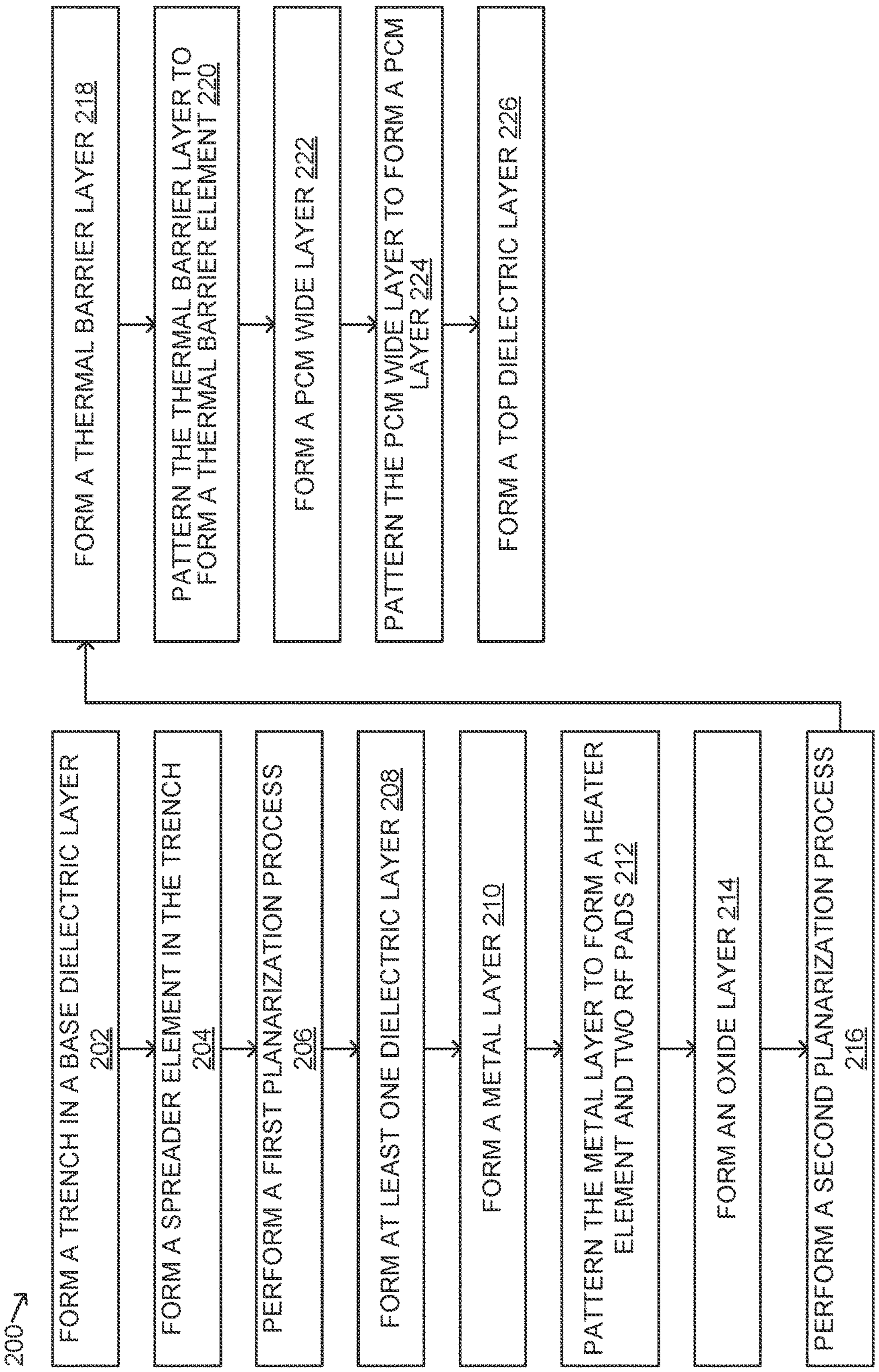

200
FORM A TRENCH IN A BASE DIELECTRIC LAYER 202
FORM A SPREADER ELEMENT IN THE TRENCH 204
PERFORM A FIRST PLANARIZATION PROCESS 206
FORM AT LEAST ONE DIELECTRIC LAYER 208
FORM A METAL LAYER 210
PATTERN THE METAL LAYER TO FORM A HEATER ELEMENT AND TWO RF PADS 212
FORM AN OXIDE LAYER 214
PERFORM A SECOND PLANARIZATION PROCESS 216
FORM A THERMAL BARRIER LAYER 218
PATTERN THE THERMAL BARRIER LAYER TO FORM A THERMAL BARRIER ELEMENT 220
FORM A PCM WIDE LAYER 222
PATTERN THE PCM WIDE LAYER TO FORM A PCM LAYER 224
FORM A TOP DIELECTRIC LAYER 226

FIG. 2

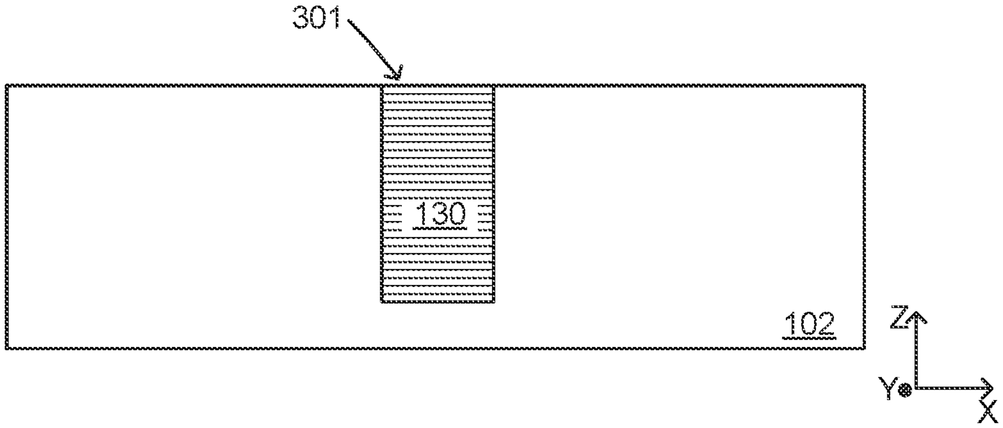


FIG. 3A

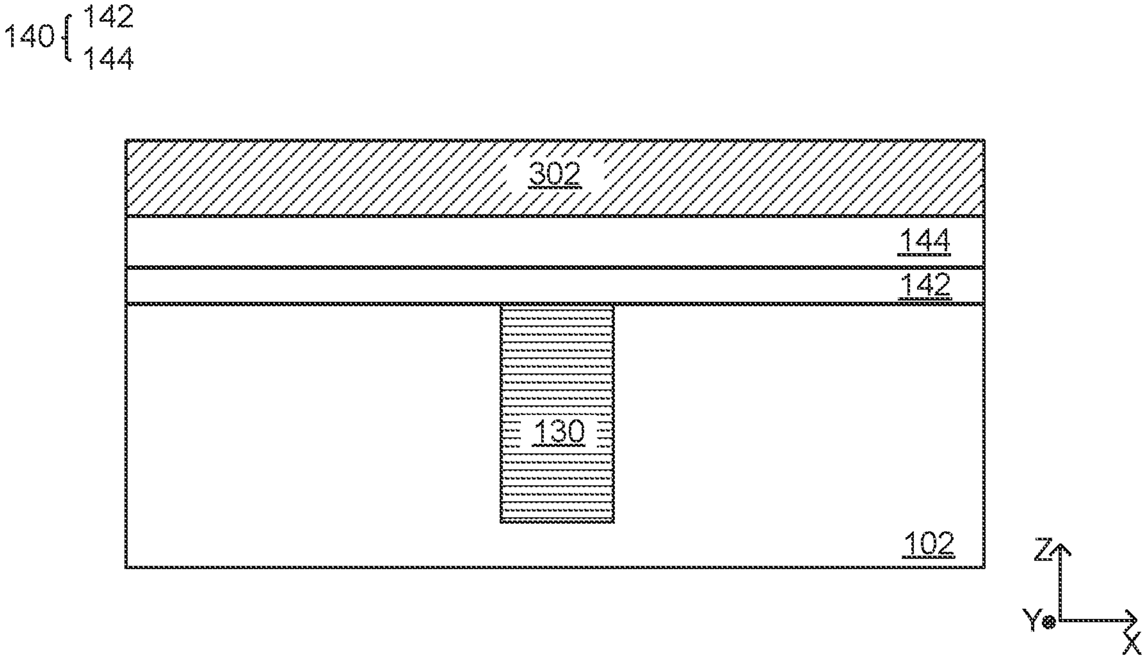


FIG. 3B

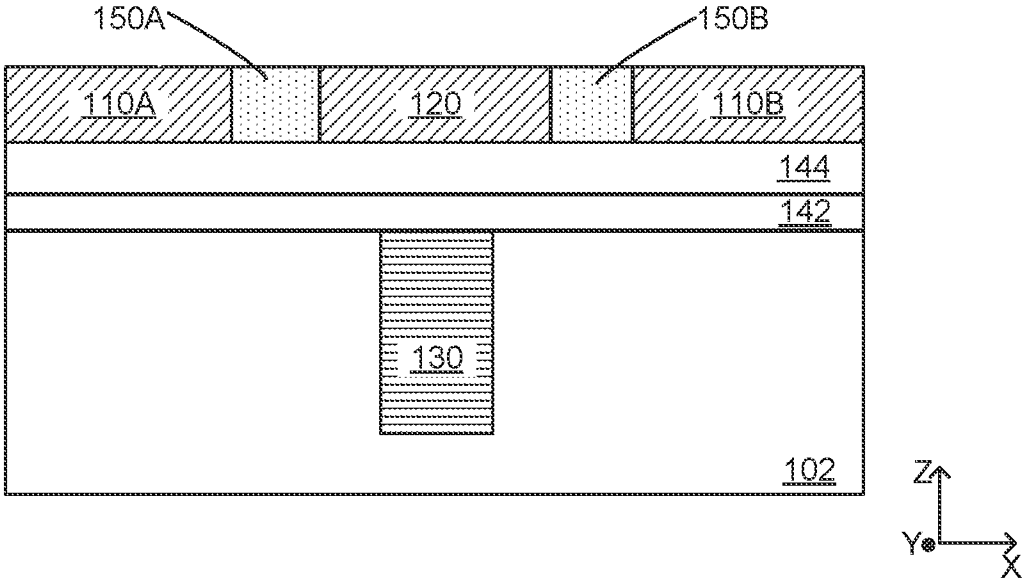

150A
150B
110A
120
110B
144
142
130
102
Z
Y
X

FIG. 3C

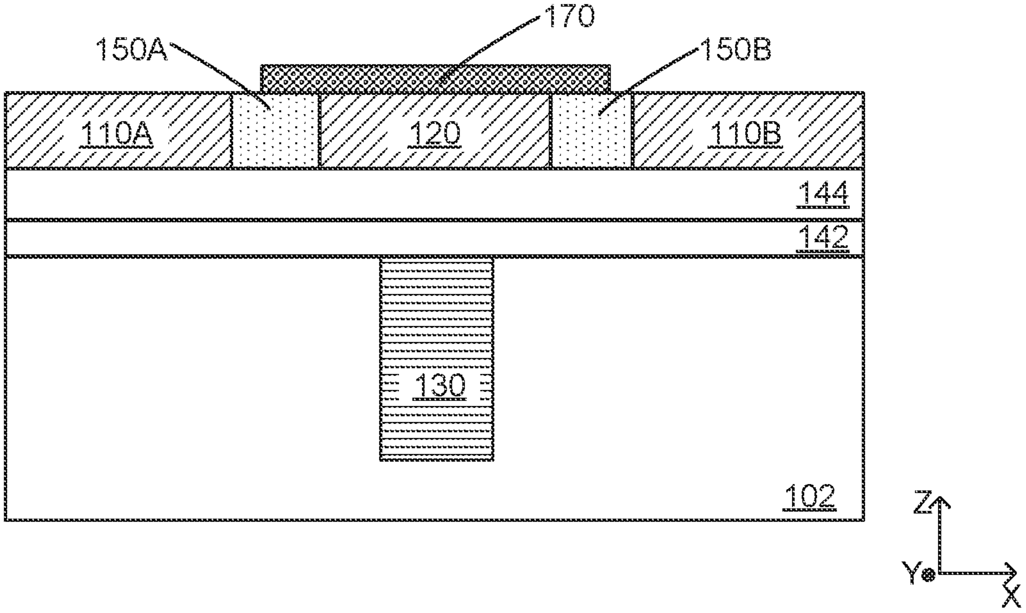

170
150A
150B
110A
120
110B
144
142
130
102
Z
Y
X

FIG. 3D

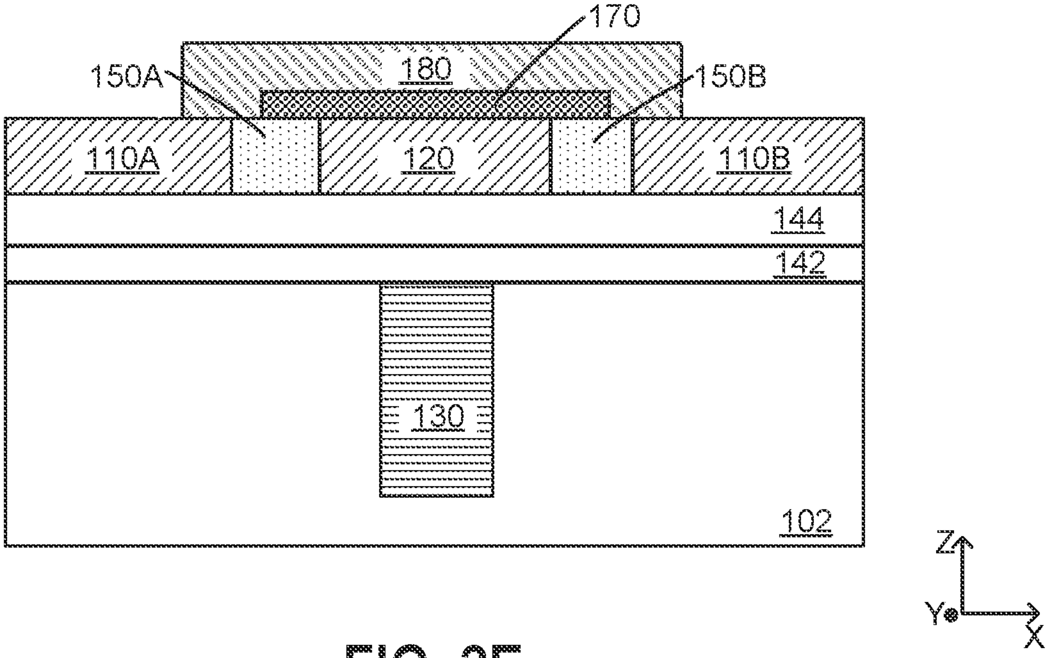

170
150A
180
150B
110A
120
110B
144
142
130
102
Z
Y
X

FIG. 3E

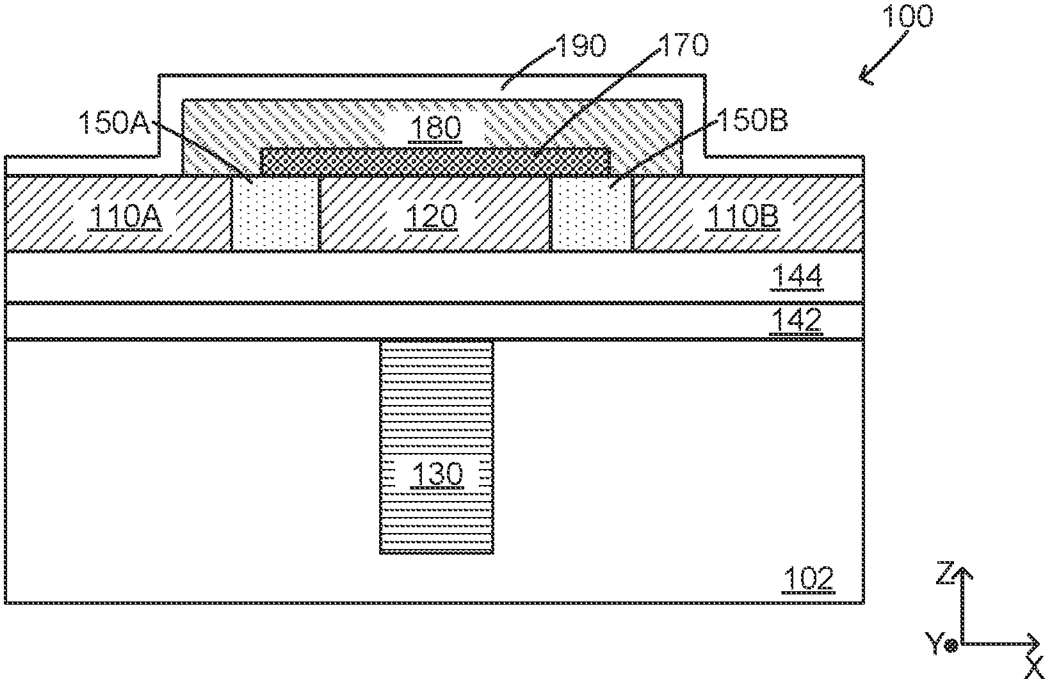

100
190
170
150A
180
150B
110A
120
110B
144
142
130
102
Z
Y
X

FIG. 3F

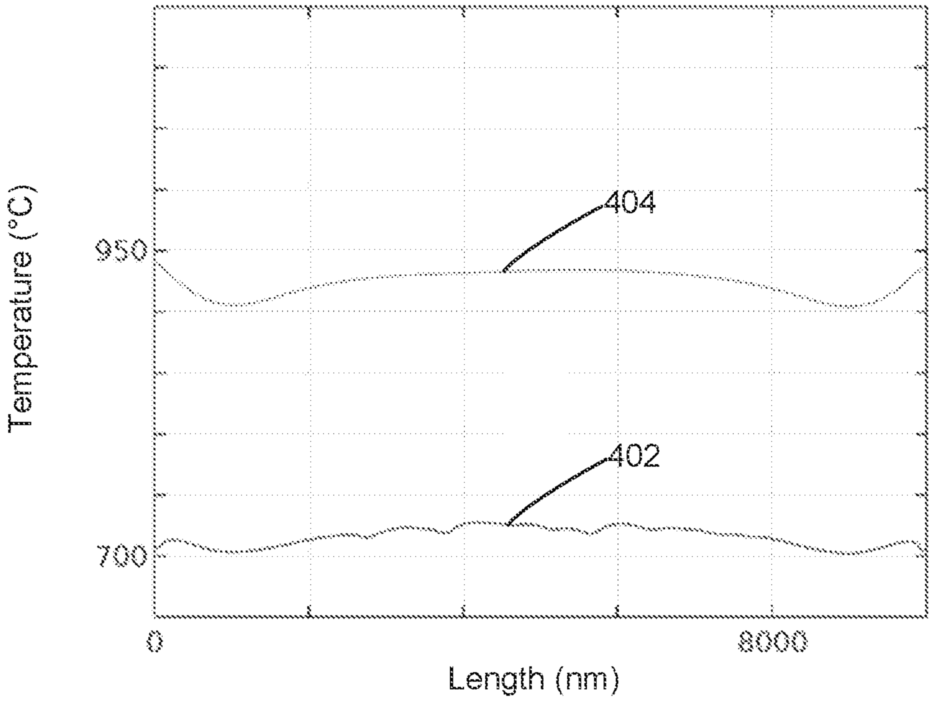

Temperature (°C)
950
700
404
402
0
8000
Length (nm)

FIG. 4A

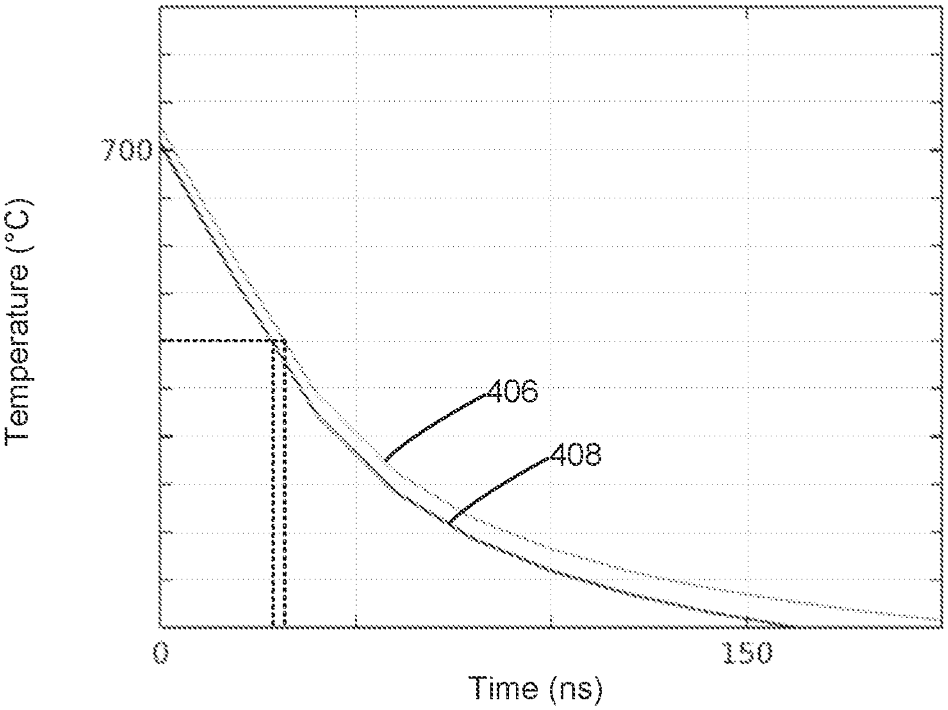

Temperature (°C)
700
406
408
0
150
Time (ns)

FIG. 4B

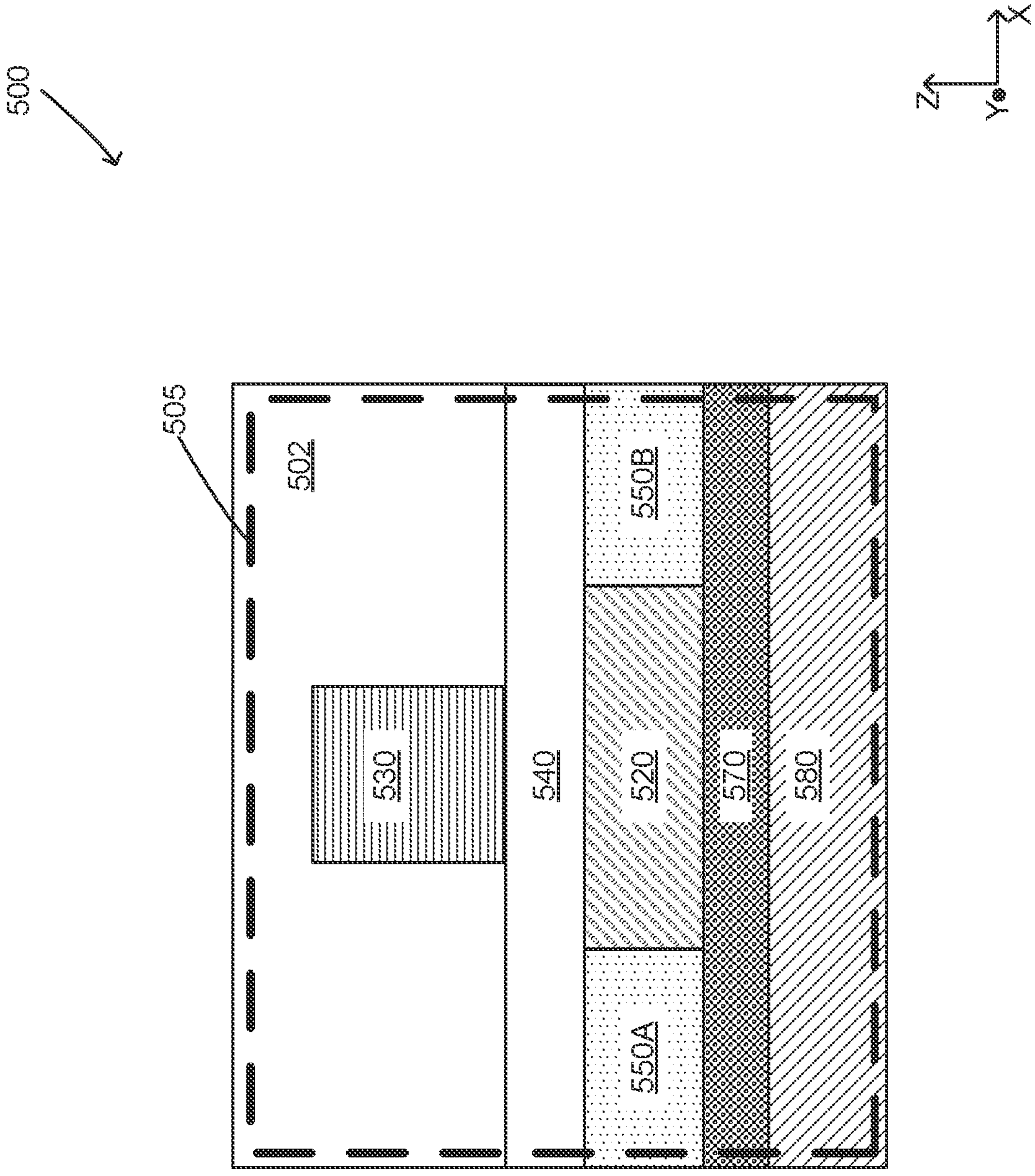


FIG. 5

PHASE-CHANGE MATERIAL (PCM) RADIO FREQUENCY (RF) SWITCHING DEVICE WITH NOVEL SPREADER DESIGN

FIELD

[0001] Embodiments of the present disclosure relate generally to radio frequency (RF) devices, and more particularly to phase-change material (PCM) RF switching devices.

BACKGROUND

[0002] The semiconductor industry has experienced rapid growth due to ongoing improvements in the integration density of a variety of electronic components (e.g., transistors, diodes, resistors, capacitors, etc.). For the most part, improvement in integration density has resulted from iterative reduction of minimum feature size, which allows more components to be integrated into a given area.

BRIEF DESCRIPTION OF THE DRAWINGS

[0003] Aspects of the present disclosure are best understood from the following detailed description when read with the accompanying figures. It is noted that, in accordance with the standard practice in the industry, various features are not drawn to scale. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.

[0004] FIG. **1**A is a cross-sectional diagram illustrating an example PCM RF switch in accordance with some embodiments.

[0005] FIG. **1**B is a diagram illustrating the layout corresponding to the example PCM RF switch **100** shown in FIG. **1**A in accordance with some embodiments.

[0006] FIG. **1**C is a diagram illustrating an example spreader element in accordance with some embodiments.

[0007] FIG. **1**D is a diagram illustrating another example spreader element in accordance with some embodiments.

[0008] FIG. **1**E is a diagram illustrating yet another example spreader element in accordance with some embodiments.

[0009] FIG. **2** is a flowchart diagram illustrating an example method for fabricating a PCM RF switch in accordance with some embodiments.

[0010] FIGS. **3**A-**3**F are cross-sectional views of a portion of the PCM RF switch at various stages of fabrication in accordance with some embodiments.

[0011] FIG. **4**A is a diagram illustrating an example temperature profile of a PCM layer and a thermal barrier element of a PCM RF switch in accordance with some embodiments.

[0012] FIG. **4**B is a diagram illustrating an example quench speed of a PCM layer of a PCM RF switch in accordance with some embodiments.

[0013] FIG. **5** is a cross-sectional diagram illustrating a portion of an example PCM RF switch in accordance with some embodiments.

DETAILED DESCRIPTION OF THE INVENTION

[0014] The following disclosure provides many different embodiments, or examples, for implementing different features of the subject matter provided. Specific examples of components and arrangements are described below to simplify the present disclosure. These are, of course, merely examples and are not intended to be limiting. For example, the formation of a first feature over or on a second feature in the description that follows may include embodiments in which the first and second features are formed in direct contact, and may also include embodiments in which additional features may be formed between the first and second features, such that the first and second features may not be in direct contact. In addition, the present disclosure may repeat reference numerals and/or letters in the various examples. This repetition is for the purpose of simplicity and clarity and does not in itself dictate a relationship between the various embodiments and/or configurations discussed.

[0015] Further, 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 or feature's relationship to another element(s) or feature(s) as illustrated in the figures. The spatially relative terms are intended to encompass different orientations of the device in use or operation in addition to the orientation depicted in the figures. The apparatus may be otherwise oriented (rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein may likewise be interpreted accordingly.

[0016] In addition, source/drain region(s) may refer to a source or a drain, individually or collectively dependent upon the context. For example, a device may include a first source/drain region and a second source/drain region, among other components. The first source/drain region may be a source region, whereas the second source/drain region may be a drain region, or vice versa. One of ordinary skill in the art would recognize many variations, modifications, and alternatives.

[0017] Some embodiments of the disclosure are described. Additional operations can be provided before, during, and/or after the stages described in these embodiments. Some of the stages that are described can be replaced or eliminated for different embodiments. Some of the features described below can be replaced or eliminated and additional features can be added for different embodiments. Although some embodiments are discussed with operations performed in a particular order, these operations may be performed in another logical order.

Overview

[0018] A radio frequency (RF) switch or a microwave switch (sometimes also referred to as an "RF switching device" or a "microwave switching device") is a device to route high-frequency signals through transmission paths. RF or microwave switches are used extensively in microwave test systems for signal routing between instruments and devices under test (DUT). In addition, RF switches are widely used in wireless communication.

[0019] A phase-change material (PCM) RF switch is a new type of RF switch. PCM RF switches operate based on the PCM switching mechanism. The PCM switching mechanism is a mechanism of reversible switching of a PCM between resistive states, i.e., an amorphous OFF state or phase (i.e., a high resistance state) and a crystalline ON state or phase (i.e., a low resistance state). The reversible switching is enabled by changing the phase of the PCM, which includes a structure that may change phase between amorphous and crystalline based on, for example, temperature change sequences via joule heating. Joule heating involves the heat that is produced during the flow of an (electric) current through, for example, a conductive material. As the PCM changes phase from crystalline to amorphous, for example, due to heating and cooling sequences controlled by, for example, applied voltage biases from the control circuitry, the resistance of the PCM changes from low to high, respectively. Accordingly, a PCM RF switch can be turned on or off by switching between the high resistance state and the low resistance state.

[0020] Joule heating is typically controlled by temperature pulses (implemented by current pulses) with the desired pulse width and the desired falling time. In the reset operation (i.e., changing from the crystalline state to the amorphous state), a high current is used to raise the temperature of the PCM above its melting temperature, with a fast cooling (i.e., a relatively short falling time) to quench the PCM to prevent re-crystallization. In the set operation (i.e., changing from the amorphous state to the crystalline state), a medium current is used to raise the temperature of the PCM above its crystallization temperature but below its melting temperature. The pulse width is relatively long for nucleation formation, while the falling time is relatively long for crystal growth.

[0021] In some implementations, a spreader element is disposed in the PCM RF switch to facilitate the dissipation of the heat generated by a heater element used for Joule heating. The spreader element can improve the quench speed, thus preventing reset failure (i.e., an unsuccessful attempt to change from the crystalline state to the amorphous state) of the PCM RF switch.

[0022] Conventionally, the spreader element is elongated and has a rectangular shape in a horizontal plane and extends in a horizontal direction. As a result, the temperature profile of the PCM layer is nonuniform along the extension direction of the spreader element. The temperature at the center of the PCM layer is typically lower than the temperature at the two ends or edges of the PCM layer, along the extension direction of the spreader element. In one example, the temperature difference between the center and the edges is about 100° C.

[0023] The nonuniform temperature profile may result in nonuniform quench speed. The center of the PCM layer is quenched faster than the edges of the PCM layer. That is, the temperature of the center of the PCM layer falls faster than the temperature of the edges of the PCM layer does, along the extension direction of the spreader element. As a result, the edges of the PCM layers are prone to re-crystallization as the temperature is above the crystallization temperature. Consequently, the center of the PCM layer may be in the amorphous state, while the edges of the PCM layer may be in the crystalline state. The coexistence of the amorphous state and the crystalline state may cause failure of the functioning of the PCM RF switch.

[0024] On the other hand, the nonuniform temperature profile may lead to thermal damage occurring at the thermal barrier layer disposed between the PCM layer and the heater element. The damage may cause poor endurance of the PCM RF switch.

[0025] In accordance with some aspects of the disclosure, a phase-change material (PCM) switching device is provided. The PCM switching device includes, among other components, a base dielectric layer, a spreader element, a heater element, two RF pads, a thermal barrier element, a PCM layer, and a top dielectric layer. The spreader element is operable to provide a heat dissipation path from the PCM layer and the heater element to the spreader element. The spreader element is elongated and extends in a first horizontal direction. Unlike the conventional the spreader element, the spreader element has nonuniform widths in a second horizontal direction perpendicular to the first horizontal direction. Specifically, the width at the edges of the spreader element is larger than the width at the center of the spreader element.

[0026] In one embodiment, the spreader element includes a central portion, a first end portion, and a second end portion. The central portion extends in the first horizontal direction and has a first width in a second horizontal direction; the first end portion has a second width in the second horizontal direction; the second end portion has a third width in the second horizontal direction. At least one of the second width and the third width is larger than the first width.

[0027] As a result, heat dissipation at the edges of PCM layer in the first horizontal direction is increased due to the enlarged area. Therefore, the temperature profile of the PCM layer becomes more uniform along the extension direction of the spreader element (i.e., in the first horizontal direction). The more uniform temperature profile results in more uniform quench speed of the PCM layer in the Y-direction. The risk of re-crystallization in the reset operation is mitigated. Consequently, the chance of the coexistence of the amorphous state and the crystalline state is reduced, and the thermal stability of the PCM RF switch is improved.

[0028] Details of the PCM switching device and these benefits will be described below with references to FIGS. **1A-5**.

Example PCM RF Switch

[0029] FIG. **1**A is a cross-sectional diagram illustrating an example PCM RF switch (i.e., PCM switching device) **100** in accordance with some embodiments. FIG. **1**B is a diagram illustrating the layout **100'** corresponding to the example PCM RF switch **100** shown in FIG. **1**A in accordance with some embodiments. FIG. **1**C is a diagram illustrating an example spreader element **130** in accordance with some embodiments. FIG. **1**D is a diagram illustrating another example spreader element **130'** in accordance with some embodiments. FIG. **1**E is a diagram illustrating yet another example spreader element **130"** in accordance with some embodiments. It should be understood that FIGS. **1**A-**1**E are not drawn to scale.

[0030] In the example shown in FIGS. **1**A and **1**B, the example PCM RF switch **100** includes, among other elements, a base dielectric layer **102**, a spreader element **130**, at least one dielectric layer **140** (e.g., a first dielectric layer **142** and a second dielectric layer **144** in the example shown in FIG. **1**A), a heater element **120**, two RF pads (sometimes also referred to as "metal pads") **110**A and **110**B, two separator elements **150**A and **150**B, a thermal barrier element **170**, a PCM layer **180**, and a top dielectric layer **190**. It should be understood that the PCM RF switch **100** may include other components such as structures electrically connected to the RF pads **110**A and **110**B. It should also be understood that the PCM RF switch **100** is typically fabricated using back end of line (BEOL) of fabrication.

[0031] The spreader element **130** is disposed in the base dielectric layer **102**, which is disposed over a semiconductor substrate **101** schematically shown in FIG. **1**A. In one embodiment, the base dielectric layer **102** comprises silicon dioxide. In other embodiments, the base dielectric layer **102** comprises other suitable dielectric materials. In one embodiment, the base dielectric layer **102** is an interlayer dielectric (ILD) layer disposed in a multilayer interconnect (MLI) structure, at the back end of an integrated circuit, over a semiconductor substrate comprising, for example, silicon. It should be understood that these embodiments and examples are not intended to be limiting.

[0032] In the example shown in FIGS. **1**A and **1**B, the spreader element **130** is disposed in a trench formed in the base dielectric layer **102**. The top surface of the spreader element **130** is coplanar with the top surface of the base dielectric layer **102**. The spreader element **130** is operable to provide a heat dissipation path from the PCM layer **180** and the heater element **120** to the spreader element **130**, thereby improving the quench speed and preventing the reset failure of the PCM RF switch **100**. In one embodiment, the ratio of the height of the spreader element **130** in the vertical direction (i.e., the Z-direction shown in FIG. **1**A) to the height of the at least one dielectric layer **140** is between 0.5 and 20.

[0033] In the example shown in FIGS. **1**A and **1**B, the spreader element **130** is elongated and extends in a first horizontal direction (i.e., the Y-direction shown in FIGS. **1**A and **1**B). Unlike the conventional spreader element, which has a rectangular shape in a horizontal plane (i.e., the X-Y plane shown in FIGS. **1**A and **1**B), the spreader element **130** has nonuniform widths in a second horizontal direction (i.e., the X-direction shown in FIGS. **1**A and **1**B) perpendicular to the first horizontal direction.

[0034] As shown in FIGS. **1**B and **1**C, the spreader element **130** includes a central portion **130**C, a first end portion **130**A, and a second end portion **130**B. The central portion **130**C has a rectangular shape; both the first end portion **130**A and the second end portion **130**B may have a rectangular or a square shape. The first end portion **130**A and the second end portion **130**B are located at two ends of the central portion **130**C, which extends in the Y-direction. The central portion **130**C has a first width (i.e., SW**1** shown in FIG. **1**C) in the X-direction; the first end portion **130**A has a second width (i.e., SW**2** shown in FIG. **1**C) in the X-direction; the second end portion **130**B has a third width (i.e., SW**3** shown in FIG. **1**C) in the X-direction. At least one of the second width and the third width is larger than the first width.

[0035] In some embodiments, the second width is the same as the third width. In some embodiments, the ratio of the second width to the first width (i.e., SW**2**/SW**1**) is between 1.2 and 2, and the ratio of the third width to the first width (i.e., SW**3**/SW**1**) is between 1.2 and 2. It should be understood that these embodiments are exemplary rather than limiting, and other ratio values may be employed in other embodiments.

[0036] In other embodiments, the second width is different from the third width. In some embodiments, the second width is larger than the third width, and the third width is larger than the first width. In some embodiments, both the ratio of the second width to the first width (i.e., SW**2**/SW**1**) and the ratio of the third width to the first width (i.e., SW**3**/SW**1**) is between 1.2 and 2. It should be understood that these embodiments are exemplary rather than limiting, and other ratio values may be employed in other embodiments.

[0037] Since at least one of the second width and the third width is larger than the first width, heat dissipation at the edges of PCM layer **180** in the Y-direction is increased due to the enlarged area. As a result, the temperature profile of the PCM layer **180** becomes more uniform along the extension direction of the spreader element (i.e., in the Y-direction shown in FIGS. **1**A and **1**B). In one example, the temperature difference between the center and the edges is about 30° C., which is significantly lower than the 100° C. temperature difference in the conventional situation.

[0038] The more uniform temperature profile results in more uniform quench speed of the PCM layer **180** in the Y-direction. The risk of re-crystallization in the reset operation is mitigated. Consequently, the chance of the coexistence of the amorphous state and the crystalline state is reduced, and the thermal stability of the PCM RF switch **100** is improved.

[0039] In the example shown in FIG. **1**C, the spreader element **130** has a first length (i.e., SL**1** shown in FIG. **1**C) in the Y-direction, whereas the first end portion **130**A and the second end portion **130**B have a second length (i.e., SL**2** shown in FIG. **1**C) and a third length (i.e., SL**3** shown in FIG. **1**C), respectively, in the Y-direction. In some embodiments, the ratio of the sum of the second length and the third length to the first length (i.e., (SL**2**+SL**3**) SL**1**) is smaller than 0.5, especially when a fourth width (i.e., DW shown in FIG. **1**C) in the Y-direction is larger than 3 μm. It should be understood that these embodiments are exemplary rather than limiting, and other ratio values may be employed in other embodiments.

[0040] In the example shown in FIG. **1**C, the PCM layer **180** has a fourth width (i.e., DW shown in FIG. **1**C) in the Y-direction. In some embodiments, the ratio of the first length to the fourth width (i.e., SL**1** DW) is larger than 0.8. It should be understood that these embodiments are exemplary rather than limiting, and other ratio values may be employed in other embodiments.

[0041] In one embodiment, the spreader element **130** comprises copper (Cu). In another embodiment, the spreader element **130** comprises aluminum copper alloy (AlCu). In yet another embodiment, the spreader element **130** comprises tungsten (W). In still another embodiment, the spreader element **130** comprises gold (Au). It should be understood that these embodiments are exemplary rather than limiting, and other materials may be employed in other embodiments.

[0042] The first dielectric layer **142** is disposed on the top surface of the base dielectric layer **102**. The second dielectric layer **144** is disposed on the first dielectric layer **142**. In one embodiment, the first dielectric layer **142** is an etching stop layer, and the second dielectric layer **144** is an oxide layer. In one example, the etching stop layer is a silicon carbide (SiC) layer. It should be understood that the at least one dielectric layer **140** may include one dielectric layer or more than two dielectric layers in other embodiments. Each of the at least one dielectric layer **140** may comprise one of the following: silicon dioxide, silicon carbide, silicon nitride, and aluminum nitride.

[0043] In the example shown in FIGS. **1**A and **1**B, the heater element **120** is disposed on the second dielectric layer **144** and over the spreader element **130**. That is, the heater element **120** and the spreader element **130** are substantially aligned in the X-direction, which facilitates good heat dissipation. As shown in FIG. **1**B, the heater element **120**

includes a first end portion (sometimes also referred to as a "first heat pad") **120**A, a second end portion (sometimes also referred to as a "second heat pad") **120**B, and an elongated portion **120**C. The elongated portion **120**C extends in the Y-direction. When a voltage is applied, electric current flows between the first end portion **120**A and the second end portion **120**B of the heater element **120** through the elongated portion **120**C. As mentioned above, the heat generated by the heater element **120** can be controlled by the electric current.

[0044] It is advantageous that the material of the heater element **120** has a relatively high thermal conductivity and a relatively low electrical resistivity. The relatively high thermal conductivity contributes to better thermal transmission efficiency, whereas the relatively low electrical resistivity contributes to a higher write operation efficiency.

[0045] In some embodiments, the candidate materials of the heater element **120** include tungsten (W), titanium (Ti), aluminum (Al), and tantalum (Ta). Using the coefficient of linear thermal expansion (CLTE) as the measurement, the CLTE of tungsten (W) is 4.5×10^{-6} K^{-1}; the CLTE of titanium (Ti) is 8.6×10^{-6} K^{-1}; the CLTE of aluminum (Al) is 23.1×10^{-6} K^{-1}; the CLTE of tantalum (Ta) is 6.4×10^{-6} K^{-1}.

[0046] In the example shown in FIGS. **1**A and **1**B, the RF pads **110**A and **110**B are disposed on the second dielectric layer **144**. The RF pad **110**A is disposed at a first side (e.g., the left side) of the heater element **120** in the X-direction, with a separator element **150**A therebetween; the RF pad **110**B is disposed at a second side (e.g., the right side) of the heater element **120** in the X-direction, with a separator element **150**B therebetween. In other words, the RF pad **110**A and the RF pad **110**B are disposed on the second dielectric layer **144** at two sides of the heater element **120** in the X-direction, respectively. Each of the separator elements **150**A and **150**B comprise a dielectric material such as silicon dioxide. As mentioned above, other components such as structures (e.g., vias) electrically connected to the RF pads **110**A and **110**B can be utilized to electrically connect the PCM RF switch **100** to, for example, a circuit. In other words, the electric signal passes through the PCM layer **180**, in the X-direction, from the RF pad **110**A t the RF pad **110**B, or vice versa.

[0047] As shown in FIGS. **1**A and **1**B, each of the RF pads **110**A and **110**B is in contact with the PCM layer **180**. Therefore, there is an electrical path (i.e., the read path) from the RF pad **110**A, through the PCM layer **180**, to the RF pad **110**B. The read path is separated from the write path. When the PCM layer **180** is in the amorphous state, the electrical path is cut off, and the PCM RF switch **100** is turned off. When the PCM layer **180** is in the crystalline state, the electrical path is created, and the PCM RF switch **100** is turned on.

[0048] In one embodiment, the heater element **120** and the RF pads **110**A and **110**B are made of the same material, such as tungsten (W), titanium (Ti), aluminum (Al), and tantalum (Ta). In one implementation, the heater element **120** and the RF pads **110**A and **110**B are fabricated in the same process by patterning a metal layer using an etching process.

[0049] In the example shown in FIGS. **1**A and **1**B, the thermal barrier element **170** is disposed on the heater element **120**. The thermal barrier element **170** is sandwiched between the heater element **120** and the PCM layer **180** in the Z-direction. The thermal barrier element **170** comprises a dielectric material such as silicon nitride. The thermal barrier element **170** is operable to insulate the heater element **120** and the PCM layer **180** and prevent phase segregation (i.e., change in the composition of the PCM layer **180**) after multiple cycles.

[0050] The PCM layer **180** is disposed on the thermal barrier element **170** and the RF pads **110**A and **110**B. Two ends of the PCM layer **180** in the X-direction are in contact with the RF pads **110**A and **110**B, respectively. Specifically, a first end of the PCM layer **180** in the X-direction is disposed on and electrically connected to the RF pad **110**A, and a second end of the PCM layer **180** in the X-direction is disposed on and electrically connected to the RF pad **110**B. A central region of the PCM layer **180** between the first end and the second end is above the top surface of the thermal barrier element **170**.

[0051] As described above, the resistive states of the PCM layer **180** can go through reversible switching between the amorphous state and the crystalline state. That is, the PCM layer **180** comprises a PCM operable to switch between an amorphous state and a crystalline state in response to heat generated by the heater element **120**. As the PCM layer **180** changes phase between the crystalline state and the amorphous state, the PCM RF switch **100** is turned on or turned off accordingly.

[0052] In some examples, the PCM of the PCM layer **180** comprises one or more layers of a binary system of Ga—Sb, In—Sb, In—Se, Sb—Te, Ge—Te, and Ge—Sb; a ternary system of Ge—Sb—Te, In—Sb—Te, Ga—Se—Te, Sn—Sb—Te, In—Sb—Ge, and Ga—Sb—Te; a quaternary system of Ag—In—Sb—Te, Ge—Sn—Sb—Te, Ge—Sb—Se—Te, Te—Ge—Sb—S, Ge—Sb—Te—O, and Ge—Sb—Te—N; a chalcogenide alloy containing one or more elements from Group VI of the periodic table, a Ge—Sb—Te alloy, $GezSb_2Te_5$, tungsten oxide, nickel oxide, copper oxide, or combinations thereof. In one embodiment, the PCM of the PCM layer **180** comprises germanium telluride (GeTe). In one embodiment, the PCM of the PCM layer **180** comprises antimony telluride (Sb_2Te_3). It should be understood that these materials are exemplary rather than limiting. In some implementations, the PCM layer **180** is formed by chemical vapor deposition (CVD), physical vapor deposition (PVD), pulsed laser deposition (PLD), sputtering, atomic layer deposition (ALD), or any other suitable thin film deposition processes.

[0053] The phase transition between the crystalline state and the amorphous state of the PCM layer **180** is related to the interplay between the long-range order and the short-range order of the structure of the material of the PCM layer **180**. For example, the collapse of the long-range order generates the amorphous state. The long-range order in the crystalline state facilitates electrical conduction, while the amorphous state impedes electrical conduction and results in high electrical resistance. To tune the properties of the PCM layer **180** for different needs, the material of the PCM layer **180** may be doped with various elements at different amounts to adjust the proportion of the short-range order and the long-range order inside the bonding structure of the material. The doped element may be any element used for semiconductor doping through the use of, for example, ion implantation or diffusion.

[0054] The top dielectric layer **190** is disposed on the PCM layer **180** and the RF pads **110**A and **110**B. The top dielectric layer **190** functions as a protective layer that prevents the PCM layer **180** from being, for example, oxidized. In one embodiment, the top dielectric layer **190** comprises silicon nitride. It should be understood that other materials can be employed in other embodiments.

[0055] In the example shown in FIG. **1**D, the spreader element **130'** includes a central portion **130**C, a first end portion **130**A, and a second end portion **130**B. The central portion **130**C has a rectangular shape; the first end portion **130**A and the second end portion **130**B have a trapezoid shape. The first end portion **130**A and the second end portion **130**B are located at two ends of the central portion **130**C, which extends in the Y-direction. The central portion **130**C has a first width (i.e., SW**1** shown in FIG. **1**D) in the X-direction; the first end portion **130**A has a second width (i.e., SW**2** shown in FIG. **1**D) in the X-direction; the second end portion **130**B has a third width (i.e., SW**3** shown in FIG. **1**D) in the X-direction. Likewise, at least one of the second width and the third width is larger than the first width.

[0056] In some embodiments, the second width is the same as the third width. In some embodiments, the ratio of the second width to the first width (i.e., SW**2**/SW**1**) is between 1.2 and 2, and the ratio of the third width to the first width (i.e., SW**3**/SW**1**) is between 1.2 and 2. It should be understood that these embodiments are exemplary rather than limiting, and other ratio values may be employed in other embodiments.

[0057] In other embodiments, the second width is different from the third width. In some embodiments, the second width is larger than the third width, and the third width is larger than the first width. In some embodiments, both the ratio of the second width to the first width (i.e., SW**2**/SW**1**) and the ratio of the third width to the first width (i.e., SW**3**/SW**1**) is between 1.2 and 2. It should be understood that these embodiments are exemplary rather than limiting, and other ratio values may be employed in other embodiments.

[0058] In the example shown in FIG. **1**D, the spreader element **130** has a first length (i.e., SL**1** shown in FIG. **1**D) in the Y-direction, whereas the first end portion **130**A and the second end portion **130**B have a second length (i.e., SL**2** shown in FIG. **1**D) and a third length (i.e., SL**3** shown in FIG. **1**D), respectively, in the Y-direction. In some embodiments, the ratio of the sum of the second length and the third length to the first length (i.e., (SL**2**+SL**3**) SL**1**) is smaller than 0.5, especially when a fourth width (i.e., DW shown in FIG. **1**C) in the Y-direction is larger than 3 μm. It should be understood that these embodiments are exemplary rather than limiting, and other ratio values may be employed in other embodiments.

[0059] In the example shown in FIG. **1**E, the spreader element **130"** includes a central portion **130**C, a first end portion **130**A, and a second end portion **130**B. The central portion **130**C has a rectangular shape; the first end portion **130**A and the second end portion **130**B have a circular shape. The first end portion **130**A and the second end portion **130**B are located at two ends of the central portion **130**C, which extends in the Y-direction. The central portion **130**C has a first width (i.e., SW**1** shown in FIG. **1**E) in the X-direction; the first end portion **130**A has a second width (i.e., SW**2** shown in FIG. **1**E) in the X-direction; the second end portion **130**B has a third width (i.e., SW**3** shown in FIG. **1**E) in the X-direction. Likewise, at least one of the second width and the third width is larger than the first width.

[0060] In some embodiments, the second width is the same as the third width. In some embodiments, the ratio of the second width to the first width (i.e., SW**2**/SW**1**) is between 1.2 and 2, and the ratio of the third width to the first width (i.e., SW**3**/SW**1**) is between 1.2 and 2. It should be understood that these embodiments are exemplary rather than limiting, and other ratio values may be employed in other embodiments.

[0061] In other embodiments, the second width is different from the third width. In some embodiments, the second width is larger than the third width, and the third width is larger than the first width. In some embodiments, both the ratio of the second width to the first width (i.e., SW**2**/SW**1**) and the ratio of the third width to the first width (i.e., SW**3**/SW**1**) is between 1.2 and 2. It should be understood that these embodiments are exemplary rather than limiting, and other ratio values may be employed in other embodiments.

[0062] In the example shown in FIG. **1**E, the spreader element **130** has a first length (i.e., SL**1** shown in FIG. **1**E) in the Y-direction, whereas the first end portion **130**A and the second end portion **130**B have a second length (i.e., SL**2** shown in FIG. **1**E) and a third length (i.e., SL**3** shown in FIG. **1**E), respectively, in the Y-direction. In some embodiments, the ratio of the sum of the second length and the third length to the first length (i.e., (SL**2**+SL**3**)/SL**1**) is smaller than 0.5, especially when a fourth width (i.e., DW shown in FIG. **1**C) in the Y-direction is larger than 3 μm. It should be understood that these embodiments are exemplary rather than limiting, and other ratio values may be employed in other embodiments.

[0063] For both spreader elements **130'** and **130"**, since the second width is larger than the first width, heat dissipation at the edges of PCM layer **180** in the Y-direction is increased due to the enlarged area. As a result, the temperature profile of the PCM layer **180** becomes more uniform along the extension direction of the spreader element (i.e., in the Y-direction shown in FIGS. **1**A and **1**B). In one example, the temperature difference between the center and the edges is about 30° C., which is significantly lower than the 100° C. temperature difference in the conventional situation.

[0064] The more uniform temperature profile results in more uniform quench speed of the PCM layer **180** in the Y-direction. The risk of re-crystallization in the reset operation is mitigated. Consequently, the chance of the coexistence of the amorphous state and the crystalline state is reduced, and the thermal stability of the PCM RF switch **100** is improved.

[0065] It should be understood that the embodiments shown in FIGS. **1**C-**1**E are exemplary rather than limiting. Other geometries of the first end portion **130**A and the second end portion **130**B may be employed in other embodiments, as long as the first end portion **130**A and the second end portion **130**B may have a dimension in the X-direction that is larger than the first width (i.e., SW**1** shown in FIGS. **1**C-**1**E) of the central portion **130**C.

Example Fabrication Process

[0066] FIG. **2** is a flowchart diagram illustrating an example method **200** for fabricating a PCM RF switch in accordance with some embodiments. In the example shown in FIG. **2**, the method **200** includes operations **202**, **204**, **206**, **208**, **210**, **212**, **214**, **216**, **218**, **220**, **222**, **224**, and **226**. Additional operations may be performed. Also, it should be understood that the sequence of the various operations discussed above with reference to FIG. **2** is provided for illustrative purposes, and as such, other embodiments may utilize different sequences. These various sequences of operations are to be included within the scope of embodiments. FIGS. **3**A-**3**F are cross-sectional views of a portion of the PCM RF switch at various stages of fabrication in accordance with some embodiments.

[0067] The method **200** starts with operation **202**. At operation **202**, a trench is formed in a base dielectric layer. In one implementation, the trench is formed by patterning the base dielectric layer using an etching process. The geometry of the trench corresponds to the spreader element to be formed inside the trench. In one embodiment, the base dielectric layer comprises silicon dioxide.

[0068] At operation **204**, a spreader element is formed in the trench by filling a metal material or a metal alloy material in the trench. In one implementation, the spreader element is formed using electroplating. It should be understood that the spreader element may be formed using other suitable processes in other embodiments. In one embodiment, the spreader element comprises copper (Cu). In another embodiment, the spreader element comprises aluminum copper alloy (AlCu). In yet another embodiment, the spreader element comprises tungsten (W). In still another embodiment, the spreader element comprises gold (Au).

[0069] At operation **206**, a first planarization process is performed. In one implementation, the first planarization process is a chemical-mechanical polishing (CMP) process. After the first planarization process, the excess portion of spreader element outside the trench is removed, and a substantially flat top surface of the base dielectric layer and the spreader element is achieved.

[0070] In the example shown in FIG. **3**A, the spreader element **130** is formed in the trench **301** in the base dielectric layer **102**. The top surface of the spreader element **130** is coplanar with the top surface of the base dielectric layer **102**. Although only one cross-section is shown in FIG. **3**A, it should be understood that the spreader element **130** extends in the Y-direction shown in FIG. **3**A and has nonuniform widths in the X-direction shown in FIG. **3**A. Examples of the geometry of the spreader element **130** include those shown in FIGS. **1**C-**1**E.

[0071] At operation **208**, at least one dielectric layer is formed on the base dielectric layer and the spreader element. In one implementation, the at least one dielectric layer is formed using chemical vapor deposition (CVD). In other implementations, the at least one dielectric layer is formed using physical vapor deposition (PVD), pulsed laser deposition (PLD), sputtering, atomic layer deposition (ALD), or any other suitable processes.

[0072] At operation **210**, a metal layer is formed on the at least one dielectric layer. In one implementation, the metal layer is formed using electroplating. It should be understood that the metal layer may be formed using other suitable processes in other embodiments. The metal layer will subsequently be patterned, using an etching process, to form the heater element and the RF pads, which will be discussed below.

[0073] In the example shown in FIG. **3**B, the first dielectric layer **142** is formed on the top surface of the base dielectric layer **102**. The second dielectric layer **144** is disposed on the first dielectric layer **142**. The metal layer **302** is formed on the second dielectric layer **144**. In one embodiment, the first dielectric layer **142** is an etching stop layer, and the second dielectric layer **144** is an oxide layer. In one example, the etching stop layer is a silicon carbide (SiC) layer. In one embodiment, the metal layer **302** is a tungsten layer. In another embodiment, the metal layer **302** is a titanium layer. In yet another embodiment, the metal layer **302** is an aluminum layer. In still another embodiment, the metal layer **302** is a tantalum layer.

[0074] At operation **212**, the metal layer is patterned using an etching process. Consequently, a heater element and two RF pads are formed. In one implementation, a photoresist layer is formed on the metal layer and then patterned, using photolithography, and the exposed region of the metal layer is etched subsequently. Gaps are formed between the heater element and the two RF pads.

[0075] At operation **214**, an oxide layer is formed. The oxide layer fills the gaps between the heater element and the two RF pads. In one implementation, the oxide layer is formed using CVD. In other implementations, the oxide layer is formed using PVD, PLD, sputtering, ALD, or any other suitable processes.

[0076] At operation **216**, a second planarization process is performed. In one implementation, the second planarization process is a CMP process. After the second planarization process, the oxide layer that is outside the gaps between the heater element and the two RF pads is removed.

[0077] In the example shown in FIG. **3**C, the heater element **120** is formed on the second dielectric layer **144** and over the spreader element **130**. Although only one cross-section is shown in FIG. **3**C, it should be understood that the heater element **120** includes a first end portion (e.g., the first end portion **120**A shown in FIG. **1**B), a second end portion (e.g., the second end portion **120**B shown in FIG. **1**B), and an elongated portion (e.g., the elongated portion **120**C shown in FIG. **1**B). The RF pad **110**A is disposed at a left side of the heater element **120** in the X-direction, with a separator element **150**A therebetween; the RF pad **110**B is disposed at a right side of the heater element **120** in the X-direction, with a separator element **150**B therebetween. Each of the separator elements **150**A and **150**B comprise a dielectric material such as silicon dioxide.

[0078] At operation **218**, a thermal barrier layer is formed. In one implementation, the thermal barrier layer is formed using CVD. In other implementations, the thermal barrier layer is formed using PVD, PLD, sputtering, ALD, or any other suitable processes.

[0079] At operation **220**, the thermal barrier layer is patterned using an etching process to form a thermal barrier element. In one implementation, a photoresist layer is formed on the thermal barrier layer and then patterned, using photolithography, and the exposed region of the thermal barrier layer is etched subsequently.

[0080] In the example shown in FIG. **3**D, the thermal barrier element **170** is formed on the heater element **120**. The thermal barrier element **170** overlaps with the separator elements **150**A and **150**B at two ends in the X-direction, respectively. In one embodiment, the thermal barrier element **170** comprises a dielectric material such as silicon nitride.

[0081] At operation **222**, a PCM wide layer is formed. The PCM wide layer is formed on the thermal barrier element, the separator elements, and the RF pads. In one implementation, the PCM wide layer is formed using CVD. In other implementations, the PCM wide layer is formed using PVD, PLD, sputtering, ALD, or any other suitable thin film deposition processes.

[0082] As mentioned above, the PCM wide layer may comprise one or more layers of a binary system of Ga—Sb, In—Sb, In—Se, Sb—Te, Ge—Te, and Ge—Sb; a ternary system of Ge—Sb—Te, In—Sb—Te, Ga—Se—Te, Sn—Sb—Te, In—Sb—Ge, and Ga—Sb—Te; a quaternary system of Ag—In—Sb—Te, Ge—Sn—Sb—Te, Ge—Sb—Se—Te, Te—Ge—Sb—S, Ge—Sb—Te—O, and Ge—Sb—Te—N; a chalcogenide alloy containing one or more elements from Group VI of the periodic table, a Ge—Sb—Te alloy, $Ge_2Sb_2Te_5$, tungsten oxide, nickel oxide, copper oxide, or combinations thereof. It should be understood that these materials are exemplary rather than limiting.

[0083] At operation **224**, the PCM wide layer is patterned, using an etching process, to form a PCM layer. In one implementation, a photoresist layer is formed on the PCM layer and then patterned, using photolithography, and the exposed region of the PCM layer is etched subsequently.

[0084] In the example shown in FIG. **3**E, the PCM layer **180** is formed on the thermal barrier element **170** and the RF pads **110**A and **110**B. Two ends of the PCM layer **180** in the X-direction are in contact with the RF pads **110**A and **110**B, respectively. A central region of the PCM layer **180** between the first end and the second end is above the top surface of the thermal barrier element **170**.

[0085] At operation **226**, a top dielectric layer is formed. In one implementation, the top dielectric layer is formed using CVD. In other implementations, the top dielectric layer is formed using PVD, PLD, sputtering, ALD, or any other suitable processes. In one embodiment, the top dielectric layer comprises silicon nitride.

[0086] In the example shown in FIG. **3**F, the top dielectric layer **190** is formed on the PCM layer **180** and the RF pads **110**A and **110**B. The top dielectric layer **190** functions as a protective layer that prevents the PCM layer **180** from being, for example, oxidized.

[0087] As such, the example PCM RF switch **100** is fabricated.

Improved Temperature Profile Uniformity and Quench Speed Uniformity

[0088] FIG. **4**A is a diagram illustrating an example temperature profile of a PCM layer and a thermal barrier element of a PCM RF switch in accordance with some embodiments. In the example shown in FIG. **4**A, curve **402** is the temperature profile of a PCM layer (e.g., the PCM layer **180** shown in FIG. **1**A) of a PCM RF switch (e.g., the PCM RF switch **100** shown in FIG. **1**A); curve **404** is the temperature profile of a thermal barrier element (e.g., the thermal barrier element **170** shown in FIG. **1**A) of the PCM RF switch. The temperature of the PCM layer varies along the extension direction (e.g., the Y-direction shown in FIG. **1**A) of the spreader element (e.g., the spreader element **130** shown in FIG. **1**A). Likewise, the temperature of the thermal barrier element varies along the extension direction of the spreader element.

[0089] As mentioned above, the spreader element of a conventional PCM RF switch is elongated and has a rectangular shape in a horizontal plane and extends in a horizontal direction. As a result, the temperature profile of the PCM layer is nonuniform along the extension direction of the spreader element. The temperature at the center of the PCM layer is typically lower than the temperature at the two ends or edges of the PCM layer, along the extension direction of the spreader element. In one example, the temperature difference between the center and the edges is about 100° C.

[0090] In contrast, the spreader element (e.g., the spreader element **130** shown in FIGS. **1**A and **1**B) disclosed herein has nonuniform widths (e.g., the second width SW**2** and the first width SW**1** shown in FIG. **1**C) in a second horizontal direction (i.e., the X-direction shown in FIG. **1**C). Since the second width is larger than the first width, heat dissipation at the edges of PCM layer is increased due to the enlarged area. As a result, the temperature profile of the PCM layer becomes more uniform along the extension direction of the spreader element. In the example shown in FIG. **4**A, the temperature difference between the center and the edges of the PCM layer is about 30° C., which is significantly lower than the 100° C. temperature difference in the conventional situation. Likewise, the temperature difference between the center and the edges of the thermal barrier element is about 50° ° C., which is significantly lower than the 200° C. temperature difference in the conventional situation.

[0091] FIG. **4**B is a diagram illustrating an example quench speed of a PCM layer of a PCM RF switch in accordance with some embodiments. In the example shown in FIG. **4**B, curve **406** is the quench speed curve of the center of a PCM layer (e.g., the PCM layer **180** shown in FIG. **1**A) of a PCM RF switch (e.g., the PCM RF switch **100** shown in FIG. **1**A); curve **408** is the quench speed curve of the edges of the PCM layer of the PCM RF switch. The temperature of the center of the PCM layer and the temperature of the edges of the PCM layer drop over time.

[0092] In the example shown in FIG. **4**B, the chance of re-crystallization is relatively high when the temperature drops to 500° C. As mentioned above, the spreader element of a conventional PCM RF switch is elongated and has a rectangular shape in a horizontal plane and extends in a horizontal direction. As a result, the temperature of the center of the PCM layer and the temperature of the edges of the PCM layer do not drop at the same quench speed. The temperature of the center of the PCM layer typically drops faster than the temperature of the edges of the PCM layer, along the extension direction of the spreader element. It takes about 50 ns for the edges of the PCM layer to reach 500° C., and the quench speed deviation is relatively large.

[0093] In contrast, the spreader element (e.g., the spreader element **130** shown in FIGS. **1**A and **1**B) disclosed herein has nonuniform widths (e.g., the second width SW**2** and the first width SW**1** shown in FIG. **1**C) in a second horizontal direction (i.e., the X-direction shown in FIG. **1**C). Since the second width is larger than the first width, heat dissipation at the edges of PCM layer is increased due to enlarged area. As a result, the temperature of the edges of the PCM layer drops faster than that in a conventional situation. In the example shown in FIG. **4**B, it takes about 30 ns for the edges of the PCM layer to reach 500° C., and the quench speed deviation becomes relatively small (i.e., the curve **406** and the curve **408** become relatively closer). The risk of re-crystallization in the reset operation is mitigated.

Spreader Element Over the Heater Element

[0094] Although the spreader element **130** is below the heater element **120** in the example shown in FIG. **1**A, other designs are available in other embodiments. In an alternative embodiment, the spreader element can be disposed above the heater element, while the PCM layer is disposed below the heater element.

[0095] FIG. **5** is a cross-sectional diagram illustrating a portion **505** of an example PCM RF switch **500** in accordance with some embodiments. The portion **505** corresponds to the portion **105** shown in FIG. **1**A. In other words, the PCM RF switch **500** includes more than the portion **505** shown in FIG. **5**. For example, the PCM RF switch **500** may also include two RF pads.

[0096] In the example shown in FIG. **5**, a thermal barrier element **570** is disposed on the PCM layer **580**, and a heater element **520** is disposed on the thermal barrier element **570**. Two separator elements **550**A and **550**B are also disposed on the thermal barrier element **570**. The separator elements **550**A and **550**B are disposed on two sides of the heater element **520** in the X-direction, respectively. At least one dielectric layer **540** is disposed on the heater element **520** and the separator elements **550**A and **550**B. A spreader element **530** is disposed on the at least one dielectric layer **540**. The spreader element **530** is also disposed in a base dielectric layer **502**. The bottom surface of the spreader element **530** is coplanar with the bottom surface of the base dielectric layer **502**.

[0097] The PCM layer **580**, the thermal barrier element **570**, the heater element **520**, the separator elements **550**A and **550**B, the at least one dielectric layer **540**, the spreader element **530**, the base dielectric layer **502** are similar to the PCM layer **180**, the thermal barrier element **170**, the heater element **120**, the separator elements **150**A and **150**B, the at least one dielectric layer **140**, the spreader element **130**, the base dielectric layer **102** shown in FIG. **1**A. Therefore, details of these components are not discussed.

[0098] Likewise, the spreader element **530** is elongated and extends in the Y-direction shown in FIG. **5**, and the spreader element **530** has nonuniform widths in the X-direction shown in FIG. **5** along the Y-direction. Likewise, the spreader element **530** may include a central portion, a first end portion, and a second end portion. The first end portion and the second end portion are located at two ends of the central portion, which extends in the Y-direction shown in FIG. **5**. The central portion has a first width in the X-direction, whereas the first end portion and the second end portion may have a second width in the X-direction. The second width is larger than the first width. In some embodiments, the ratio of the second width to the first width is between 1.2 and 2. It should be understood that these embodiments are exemplary rather than limiting, and other ratio values may be employed in other embodiments.

[0099] As discussed above, since the second width is larger than the first width, heat dissipation at the edges of PCM layer **580** in the Y-direction is increased due to enlarged area. As a result, the temperature profile of the PCM layer **580** becomes more uniform along the extension direction of the spreader element (i.e., in the Y-direction shown in FIG. **5**). The more uniform temperature profile results in a more uniform quench speed of the PCM layer **580** in the Y-direction. The risk of re-crystallization in the reset operation is mitigated. Consequently, the chance of the coexistence of the amorphous state and the crystalline state is reduced, and the thermal stability of the PCM RF switch **500** is improved.

[0100] In one embodiment, the spreader element **530** comprises copper (Cu). In another embodiment, the spreader element **530** comprises aluminum copper alloy (AlCu). In yet another embodiment, the spreader element **530** comprises tungsten (W). In still another embodiment, the spreader element **530** comprises gold (Au). It should be understood that these embodiments are exemplary rather than limiting, and other materials may be employed in other embodiments.

[0101] In accordance with some aspects of the disclosure, a phase-change material (PCM) switching device is provided. The PCM switching device includes: a base dielectric layer over a semiconductor substrate; a spreader element disposed in the base dielectric layer, wherein the spreader element extends in a first horizontal direction and comprises: a central portion extending in the first horizontal direction and having a first width in a second horizontal direction perpendicular to the first horizontal direction; a first end portion at a first end of the central portion and having a second width in the second horizontal direction; and a second end portion at a second end of the central portion and having a third width in the second horizontal direction, and wherein at least one of the second width and the third width is larger than the first width; a heater element disposed over the spreader element; a thermal barrier element disposed on the heater element; and a PCM layer disposed on the thermal barrier element.

[0102] In accordance with some aspects of the disclosure, a method for fabricating a phase-change material (PCM) switching device is provided. The method includes the following operations: forming a trench in a base dielectric layer; filling a metal material or a metal alloy material in the trench to form a spreader element in the trench, wherein the spreader element extends in a first horizontal direction and comprises a central portion extending in the first horizontal direction, a first end portion at a first end of the central portion, and a second end portion at a second end of the central portion, and wherein the central portion has a first width in a second horizontal direction perpendicular to the first horizontal direction, and the first end portion has a second width in the second horizontal direction, and the second end portion has a third width in the second horizontal direction, and wherein at least one of the second width and the third width is larger than the first width; forming at least one dielectric layer on the base dielectric layer; forming a heater element and two (radio frequency) RF pads on the at least one dielectric layer; forming a thermal barrier element on the heater element; and forming a PCM layer on the thermal barrier element.

[0103] In accordance with some aspects of the disclosure, a phase-change material (PCM) switching device is provided. The PCM switching device includes: a base dielectric layer; a spreader element disposed in the base dielectric layer, wherein the spreader element extends in a first horizontal direction, and the spreader element has nonuniform widths in a second horizontal direction perpendicular to the first horizontal direction; a heater element disposed over the spreader element; a thermal barrier element disposed on the heater element; and a PCM layer disposed on the thermal barrier element.

[0104] The foregoing outlines features of several embodiments so that those skilled in the art may better understand the aspects of the present disclosure. Those skilled in the art should appreciate that they may readily use the present disclosure as a basis for designing or modifying other processes and structures for carrying out the same purposes and/or achieving the same advantages of the embodiments introduced herein. Those skilled in the art should also realize that such equivalent constructions do not depart from the spirit and scope of the present **10** disclosure, and that they may make various changes, substitutions, and alterations herein without departing from the spirit and scope of the present disclosure.

What is claimed is:

1. A phase-change material (PCM) switching device, comprising:

a base dielectric layer over a semiconductor substrate;

a spreader element disposed in the base dielectric layer, wherein the spreader element extends in a first horizontal direction and comprises:

a central portion extending in the first horizontal direction and having a first width in a second horizontal direction perpendicular to the first horizontal direction;

a first end portion at a first end of the central portion and having a second width in the second horizontal direction; and

a second end portion at a second end of the central portion and having a third width in the second horizontal direction, and wherein at least one of the second width and the third width is larger than the first width;

a heater element disposed over the spreader element;

a thermal barrier element disposed on the heater element; and

a PCM layer disposed on the thermal barrier element.

2. The PCM switching device of claim **1**, wherein the second width is equal to the third width.

3. The PCM switching device of claim **2**, wherein a ratio of the second width to the first width is between 1.2 and 2.

4. The PCM switching device of claim **1**, wherein the second width is different from the third width.

5. The PCM switching device of claim **4**, wherein the second width is larger than the third width, and the third width is larger than the first width.

6. The PCM switching device of claim **5**, wherein a ratio of the second width to the first width is between 1.2 and 2.

7. The PCM switching device of claim **1**, wherein the central portion has a rectangular shape.

8. The PCM switching device of claim **1**, wherein both the first end portion and the second end portion have a rectangular shape.

9. The PCM switching device of claim **1**, wherein at least one of the first end portion and the second end portion comprises a trapezoid shape.

10. The PCM switching device of claim **1**, wherein at least one of the first end portion and the second end portion comprises a circular shape.

11. The PCM switching device of claim **1**, further comprising:

at least one dielectric layer disposed on the base dielectric layer, wherein the heater element is disposed on the at least one dielectric layer.

12. The PCM switching device of claim **11**, further comprising:

a first radio frequency (RF) pad disposed on the at least one dielectric layer and at a first side of the heater element in the second horizontal direction, wherein the first RF pad is in contact with the PCM layer; and

a second RF pad disposed on the at least one dielectric layer and at a second side of the heater element in the second horizontal direction, wherein the second RF pad is in contact with the PCM layer.

13. The PCM switching device of claim **1**, wherein the spreader element has a first length in the first horizontal direction, and the first end portion has a second length in the first horizontal direction, and the second end portion has a third length in the first horizontal direction, and wherein a ratio of a sum of the second length and the third length to the first length is smaller than 0.5.

14. The PCM switching device of claim **13**, wherein the second length is different from the third length.

15. A method for fabricating a phase-change material (PCM) switching device, the method comprising:

forming a trench in a base dielectric layer;

filling a metal material or a metal alloy material in the trench to form a spreader element in the trench, wherein the spreader element extends in a first horizontal direction and comprises a central portion extending in the first horizontal direction, a first end portion at a first end of the central portion, and a second end portion at a second end of the central portion, and wherein the central portion has a first width in a second horizontal direction perpendicular to the first horizontal direction, and the first end portion has a second width in the second horizontal direction, and the second end portion has a third width in the second horizontal direction, and wherein at least one of the second width and the third width is larger than the first width;

forming at least one dielectric layer on the base dielectric layer;

forming a heater element and two (radio frequency) RF pads on the at least one dielectric layer;

forming a thermal barrier element on the heater element; and

forming a PCM layer on the thermal barrier element.

16. The method of claim **15**, wherein forming the at least one dielectric layer comprises:

forming a first dielectric layer on the base dielectric layer, wherein the first dielectric layer is an etching stop layer; and

forming a second dielectric layer on the first dielectric layer, wherein the second dielectric layer is an oxide layer.

17. The method of claim **15**, wherein the second width is equal to the third width, and a ratio of the second width to the first width is between 1.2 and 2.

18. A phase-change material (PCM) switching device, comprising:

a base dielectric layer;

a spreader element disposed in the base dielectric layer, wherein the spreader element extends in a first horizontal direction, and the spreader element has nonuniform widths in a second horizontal direction perpendicular to the first horizontal direction;

a heater element disposed over the spreader element;

a thermal barrier element disposed on the heater element; and

a PCM layer disposed on the thermal barrier element.

19. The PCM switching device of claim **18**, wherein the spreader element comprises:

a central portion extending in the first horizontal direction and having a first width in the second horizontal direction;

a first end portion at a first end of the central portion and having the second width in the second horizontal direction; and

a second end portion at a second end of the central portion and having a third width in the second horizontal direction, and wherein at least one of the second width and the third width is larger than the first width.

20. The PCM switching device of claim **19**, wherein a ratio of the second width to the first width is between 1.2 and 2.

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