LAMINAR FLOW RESTRICTOR

CLAIMING AN EARLIER FILING DATE

[0001] The present application is filed under Section 26(11) of the Singapore Patents Act claiming the earlier filing date of 5 August 2020 accorded to Application No. 11202200909T.

BACKGROUND OF THE INVENTION

[0002] Mass flow control has been one of the key technologies in semiconductor chip fabrication. Apparatuses for controlling mass flow are important for delivering known flow rates of process gases for semiconductor fabrication and other industrial processes. Such devices are used to measure and accurately control the flow of fluids for a variety of applications. This control may be achieved through the use of precisely calibrated laminar flow restrictors.

[0003] As the technology of chip fabrication has improved, so has the demand on the apparatuses for controlling flow. Semiconductor fabrication processes increasingly require increased performance, including more accurate measurements, lower equipment costs, improved transient response times, and more consistency in timing in the delivery of gases. In order to improve the consistency in gas delivery, improved flow restrictors are desired.

SUMMARY OF THE INVENTION

[0004] The present technology is directed to a laminar flow restrictor for use in a mass flow controller or other gas delivery device. One or more of these gas delivery devices may be used in a wide range of processes such as semiconductor chip fabrication, solar panel fabrication, etc.

[0005] In one implementation, the invention is a flow restrictor for restricting the flow of a gas. The flow restrictor has a first end, a second end, and a longitudinal axis extending from the first end to the second end. A plurality of first layers extend from the first end to the second end along the longitudinal axis. A plurality of second layers extend from the first end to the second end along the longitudinal axis. A first aperture at the first end is defined by the plurality of first layers and the plurality of second layers. A second aperture at the second end is defined by the plurality of first layers and the plurality of second layers. A flow passage is defined by the plurality of first layers and the plurality of second layers, the flow passage extending from the first aperture to the second aperture.

[0006] In another implementation, the invention is a mass flow control apparatus for delivery of a fluid, the mass flow control apparatus having a valve comprising an inlet passage, an outlet passage, a valve seat, and a closure member. The mass flow control apparatus also has a flow restrictor, the flow restrictor positioned in one of the inlet passage or the outlet passage. The flow restrictor has a first end, a second end, and a longitudinal axis extending from the first end to the second end. A plurality of layers extend substantially parallel to the longitudinal axis. A first aperture is located at the first end and a second aperture is located at the second end. A flow passage is defined by the plurality of layers, the flow passage fluidly coupled to the first aperture and the second aperture.

[0007] In yet another implementation, the invention is a method of manufacturing a flow restrictor. First, a plurality of layer blanks are provided, the layer blanks having a first edge, a second edge opposite the first edge, a third edge, a fourth edge opposite the third edge, a front face, and a rear face opposite the front face. A first cavity is formed in the front face of a first one of the plurality of layer blanks. The plurality of layer blanks are stacked. Subsequently, the plurality of layer blanks are bonded to form a resistor stack having a first unfinished end and an opposite second unfinished end. The first unfinished end of the resistor stack is formed by the first edges of the plurality of layer blanks and the second unfinished end of the resistor stack is formed by the second edges of the plurality of layer blanks. Finally, material is removed from the first unfinished end of the layer stack to expose the first cavity and form a first aperture.

[0008] Further areas of applicability of the present technology will become apparent from the detailed description provided hereinafter. It should be understood that the detailed description and specific examples, while indicating the preferred implementation, are intended for purposes of illustration only and are not intended to limit the scope of the technology.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] The invention of the present disclosure will become more fully understood from the detailed description and the accompanying drawings, wherein:

[0010] FIG. 1 is a schematic of a process utilizing one or more laminar flow restrictors.

[0011] FIG. 2 is a schematic of a mass flow controller as may be utilized in the process of FIG. 1.

[0012] FIG. 3 is a perspective view of a first embodiment of a laminar flow restrictor as may be utilized in the mass flow controller of FIG. 2.

[0013] FIG. 4 is a perspective view illustrating a portion of the layers forming the flow restrictor of FIG. 3.

[0014] FIG. 5A is an end view of the portion of the flow restrictor of FIG. 4.

[0015] FIG. 5B is a detail view of the area VB of FIG. 5A.

[0016] FIG. 6 is an exploded perspective view of the portion of the flow restrictor of FIG. 4.

[0017] FIG. 7 is a cross-sectional view of the portion of the flow restrictor of FIG. 4, taken along line VII-VII.

[0018] FIG. 8 is a top view of a first layer of the flow restrictor of FIG. 3.

[0019] FIG. 9 is a top view of a second layer of the flow restrictor of FIG. 3.

[0020] FIG. 10 is a perspective view of a second embodiment of a laminar flow restrictor.

[0021] FIG. 11 is a perspective view illustrating a portion of the layers forming the flow restrictor of FIG. 10.

[0022] FIG. 12A is an end view of the portion of the flow restrictor of FIG. 11.

[0023] FIG. 12B is a detail view of the area XIIB of FIG. 12A.

[0024] FIG. 13 is an exploded perspective view of the portion of the flow restrictor of FIG. 11.

[0025] FIG. 14 is a cross-sectional view of the portion of the flow restrictor of FIG. 11, taken along line XIV-XIV.

[0026] FIG. 15 is a top view a first layer of the flow restrictor of FIG. 10.

[0027] FIG. 16 is a top view a second layer of the flow restrictor of FIG. 10.

[0028] FIG. 17 is a perspective view of a portion of a third embodiment of a laminar flow restrictor.

[0029] FIG. 18 is an end view of the portion of the flow restrictor of FIG. 17.

[0030] FIG. 19 is an exploded perspective view of the portion of the flow restrictor of FIG. 17.

[0031] FIG. 20 is a cross-sectional view of the portion of the flow restrictor of FIG. 17, taken along line XX-XX.

[0032] FIG. 21 is a top view of a first layer of the flow restrictor of FIG. 17.

[0033] FIG. 22 is a top view of a second layer of the flow restrictor of FIG. 17.

[0034] FIG. 23 is a perspective view of a portion of a fourth embodiment of a laminar flow restrictor.

[0035] FIG. 24 is an end view of the portion of the flow restrictor of FIG. 23.

[0036] FIG. 25 is an exploded perspective view of the portion of the flow restrictor of FIG. 23.

[0037] FIG. 26 is a cross-sectional view of the portion of the flow restrictor of FIG. 23, taken along line XXVI-XXVI.

[0038] FIG. 27 is a top view of a first layer of the flow restrictor of FIG. 23.

[0039] FIG. 28 is a top view of a second layer of the flow restrictor of FIG. 23.

[0040] FIG. 29 is a top view of a third layer of the flow restrictor of FIG. 23.

[0041] FIG. 30 is a perspective view of a fifth embodiment of a laminar flow restrictor.

[0042] FIG. 31 is a perspective view illustrating a portion of the layers forming the flow restrictor of FIG. 30.

[0043] FIG. 32 is an end view of the portion of the flow restrictor of FIG. 31.

[0044] FIG. 33 is an exploded perspective view of the portion of the flow restrictor of FIG. 31.

[0045] FIG. 34 is a cross-sectional view of the portion of the flow restrictor of FIG. 31, taken along line XXXIV-XXXIV.

[0046] FIG. 35 is a top view a first layer of the flow restrictor of FIG. 31.

[0047] FIG. 36 is a top view a second layer of the flow restrictor of FIG. 31.

[0048] FIG. 37 is an exploded perspective view of a plurality of layer blanks illustrating methods of manufacturing the disclosed flow restrictors.

[0049] FIG. 38 is a top view of a first layer of the invention of FIG. 37.

[0050] FIG. 39 is a top view of a second layer of the invention of FIG. 37.

[0051] FIG. 40 is a perspective view of a resistor stack prior to finishing according to the invention of FIG. 37.

[0052] FIG. 41 is a perspective view of a resistor stack after finishing according to the invention of FIG. 37.

DETAILED DESCRIPTION

[0053] The description of illustrative embodiments according to principles of the present invention is intended to be read in connection with the accompanying drawings, which are to be considered part of the entire written description. In the description of embodiments of the invention disclosed herein, any reference to direction or orientation is merely intended for convenience of description and is not intended in any way to limit the scope of the present invention. Relative terms such as “lower,” “upper,” “horizontal,” “vertical,” “above,” “below,” “up,” “down,” “left,” “right,” “top” and “bottom” as well as derivatives thereof (e.g., “horizontally,” “downwardly,” “upwardly,” etc.) should be construed to refer to the orientation

as then described or as shown in the drawing under discussion. These relative terms are for convenience of description only and do not require that the apparatus be constructed or operated in a particular orientation unless explicitly indicated as such. Terms such as "attached," "affixed," "connected," "coupled," "interconnected," and similar refer to a relationship wherein structures are secured or attached to one another either directly or indirectly through intervening structures, as well as both movable or rigid attachments or relationships, unless expressly described otherwise. Moreover, the features and benefits of the invention are illustrated by reference to the preferred embodiments. Accordingly, the invention expressly should not be limited to such preferred embodiments illustrating some possible non-limiting combinations of features that may exist alone or in other combinations of features; the scope of the invention being defined by the claims appended hereto.

[0054] The present invention is directed to a laminar flow restrictor for use in an apparatus for controlling gas flow. In some embodiments, the apparatus may function as a mass flow controller to deliver a known mass flow of gas to a semiconductor or similar process. Semiconductor fabrication is one industry which demands high performance in control of gas flows. As semiconductor fabrication techniques have advanced, customers have recognized the need for flow control devices with increased accuracy and repeatability in the mass of the delivered gas flows. Modern semiconductor processes require that the mass of the gas flow is tightly controlled, the response time minimized, and the gas flow is highly accurate. The present invention delivers improved accuracy and repeatability in the delivered flows.

[0055] Fig. 1 shows a schematic of an exemplary processing system 1000 utilizing one or more laminar flow restrictors. The processing system 1000 may utilize a plurality of apparatus for controlling flow 100 fluidly coupled to a processing chamber 1300. The plurality of apparatus for controlling flow 100 are used to supply one or more different process gases to the processing chamber 1300. Articles such as semiconductors may be processed within the processing chamber 1300. Valves 1100 isolate each of the apparatus for controlling flow 100 from the processing chamber 1300, enabling each of the apparatus for controlling flow 100 to be selectively connected or isolated from the processing chamber 1300, facilitating a wide variety of different processing steps. The processing chamber 1300 may contain an applicator to apply process gases delivered by the plurality of apparatus for controlling flow 100, enabling selective or diffuse distribution of the gas supplied by the plurality of apparatus for controlling flow 100. In addition, the processing system 1000 may further comprise a vacuum source 1200 which is

isolated from the processing chamber 1300 by a valve 1100 to enable evacuation of process gases or facilitate purging one or more of the apparatus for controlling flow 100 to enable switching between process gases in the same apparatus for controlling flow 100. Optionally, the apparatus for controlling flow 100 may be mass flow controllers, flow splitters, or any other device which controls the flow of a process gas in a processing system. Furthermore, the valves 1100 may be integrated into the apparatus for controlling flow 100 if so desired.

[0056] Processes that may be performed in the processing system 100 may include wet cleaning, photolithography, ion implantation, dry etching, atomic layer etching, wet etching, plasma ashing, rapid thermal annealing, furnace annealing, thermal oxidation, chemical vapor deposition, atomic layer deposition, physical vapor deposition, molecular beam epitaxy, laser lift-off, electrochemical deposition, chemical-mechanical polishing, wafer testing, or any other process utilizing controlled volumes of a process gas.

[0057] Fig. 2 shows a schematic of an exemplary mass flow controller 101, which is one type of apparatus for controlling flow 100 that may be utilized in the processing system 1000. The mass flow controller 101 has a gas supply of a process gas fluidly coupled to an inlet 104. The inlet is fluidly coupled to a proportional valve 120 which is capable of varying the volume of process gas flowing through the proportional valve 120. The proportional valve 120 meters the mass flow of process gas which passes to the P1 volume 106. The proportional valve 120 is capable of providing proportional control of the process gas such that it need not be fully open or closed, but instead may have intermediate states to permit control of the mass flow rate of process gas.

[0058] A P1 volume 106 is fluidly coupled to the proportional valve 120, the P1 volume 106 being the sum of all the volume within the mass flow controller 101 between the proportional valve 120 and a flow restrictor 160. A pressure transducer 130 is fluidly coupled to the P1 volume 106 to enable measurement of the pressure within the P1 volume 106. An on/off valve 150 is located between the flow restrictor 160 and the proportional valve 120 and may be used to completely halt flow of the process gas out of the P1 volume 106. Optionally, the flow restrictor 160 may be located between the on/off valve 150 and the proportional valve 120 in an alternate configuration. Finally, the flow restrictor 160 is fluidly coupled to an outlet 110 of the mass flow controller 101. In the processing system, the outlet 110 is fluidly coupled to a valve 1100 or directly to the processing chamber 1300.

[0059] Internal to the first on/off valve 150 is a valve seat and a closure member. When the apparatus 100 is delivering process gas, the first on/off valve 150 is in an open state, such that

the valve seat and the closure member are not in contact. This permits flow of the process gas, and provides a negligible restriction to fluid flow. When the first on/off valve 150 is in a closed state the closure member and the valve seat are biased into contact by a spring, stopping the flow of process gas through the first on/off valve 150.

[0060] The flow restrictor 160 is used, in combination with the proportional valve 120, to meter flow of the process gas. In most embodiments, the flow restrictor 160 provides a known restriction to fluid flow. The first characterized flow restrictor 160 may be selected to have a specific flow impedance so as to deliver a desired range of mass flow rates of a given process gas. The flow restrictor 160 has a greater resistance to flow than the passages upstream and downstream of the flow restrictor 160.

[0061] Optionally, the mass flow controller 101 comprises one or more P2 pressure transducers downstream of the flow restrictor 160 and the on/off valve 150. The P2 pressure transducer is used to measure the pressure differential across the flow restrictor 160. In some embodiments, the P2 pressure downstream of the flow restrictor 160 may be obtained from another apparatus 100 connected to the processing chamber, with the readings communicated to the mass flow controller 101.

[0062] Optionally, temperature sensors may be employed to further enhance the accuracy of the mass flow controller 101. They may be mounted in the base of the mass flow controller 101 near the P1 volume 106. Additional temperature sensors may be employed in a variety of locations, including the proportional valve 120, the pressure transducer 130, and the on/off valve 150.

[0063] Turning to Figs. 3-9, a first embodiment of the flow restrictor 160 is shown in greater detail. The flow restrictor 160 is constructed as a plurality of layers forming a restrictor stack 170. The restrictor stack 170 may take the form of an elongated rectangular shape as shown in Fig. 3. The flow restrictor 160 extends from a first end 161 to a second end 162 along a longitudinal axis A-A. A plurality of layers 210 comprising flow passages are sandwiched between a plurality of outer layers 220 which do not comprise flow passages. The flow restrictor 160 has a first side 163 formed of the pluralities of layers 210, 220 and an opposite second side 164. The flow restrictor 160 further comprises a front face 165 and an opposite rear face 166. The outer layers 220 enclose the flow passages on opposite sides of the layers 210 comprising flow passages. The outer layers 220 may or may not have the same thickness as the layers 210 comprising flow passages. A selection of the layers 210 is shown in Fig. 4, which illustrates portions of the flow passages and the configuration of the layers 210. Each of the layers 210

extend from a first end 213 to a second end 214. Portions of the plurality of flow passages can be seen in Fig. 4. The details of the flow passages will be discussed in greater detail below.

[0064] Turning to Figs. 5A and 5B, the layers 210 comprise a plurality of apertures 212 formed at opposite ends 213, 214 of the layers 210. This enables gas to flow along the layers 210 from the first end 213 to the second end 214 along the longitudinal axis A-A. In alternate embodiments, the apertures 212 need not be on opposite ends and may instead be formed on adjacent sides or may be formed exclusively on a single end. The apertures 212 may also be formed so that gas flows across the shorter direction of the rectangular layers 210, perpendicular to the longitudinal axis A-A. The layers 210 also need not be rectangular and may be square or any other desired shape. It is further contemplated that an aperture may be formed into the plane of the layers 210, permitting gas to flow perpendicular to the planes of the layers 210, then turn a corner and flow in the plane of the layers 210. The specific arrangement of the apertures 212, the shape of the layers 210, and the shape of the resulting flow restrictor 160 may be adapted as desired depending on the shape of the flow passage which receives the resulting flow restrictor 160. It is even contemplated that the flow restrictor 160 may have an annular configuration, with apertures 212 formed into a circumference of the flow restrictor 160 and/or apertures 212 formed so that gas flows perpendicular to the planes of some or all of the layers 210.

[0065] Fig. 6 shows an exploded view of the layers 210. The layers 210 comprise two first layers 230 and two second layers 260. As best seen in Figs. 8 and 9, the first layer 230 has a first side 231, a second side 232, a third side 233, a fourth side 234, a front face 235, and an opposite rear face 236. The second layer 260 has a first side 261, a second side 262, a third side 263, a fourth side 264, a front face 265, and an opposite rear face 266. The first layer 230 has a series of flow passages comprising entry passages 237, U passages 238, and longitudinal passages 239. The entry passages and the U passages are each only formed into a portion of the thickness of the first layer 230 while the longitudinal passages 239 extend through the entirety of the thickness of the first layer 230. The second layer 260 also has entry passages 267 and U passages 268 formed into the front face 265 that correspond to the entry passages 237 and U passages 238 of the first layer 240. When a first layer 230 and a second layer 260 are stacked with the front faces 235, 265 facing one another, the entry passages 237, 267 form apertures 212 on the first and second sides 231, 261, 232, 262 of the layers 230, 260. As is best shown in Fig. 7, in combination with additional first layers 230 and second layers 260, a plurality of flow passages 270 are formed,

extending from apertures 212 on one end 213 of the plurality of layers 210 to the opposite second end 214 of the plurality of layers 210.

[0066] Returning to Fig. 5A, the apertures 212 have a first edge 215, a second edge 216, a third edge 217, and a fourth edge 218. The first edge 215 is formed by the first layer 230, the second edge 216 is formed by the second layer 260, and the third and fourth edges 217, 218 are each formed by a portion of the first layer 230 and a portion of the second layer 260.

[0067] The flow passages 270 may be varied in any desired manner to achieve a desired flow impedance. For instance, the number of flow passages 270 may be increased or decreased by reducing or increasing the number of the plurality of layers 210. Furthermore, the length of the flow passages 270 may be increased or decreased by changing the number of times that the flow passages 270 double back on themselves, changing the resulting number of U passages 238, 268 and longitudinal passages 239. A greater or fewer number of flow passages 270 may be formed into pairs of first and second layers 230, 260. The width of the flow passages 270 may also be increased or decreased, and the thickness of the first and second layers 230, 260 may be varied. Indeed, it is not necessary that the same thickness be used for every pair of first and second layers 230, 260. Each layer within the plurality of layers 210 could be individually varied to alter the resulting flow impedance of the flow restrictor 160.

[0068] The flow restrictor 160 is manufactured by first etching each of the layers 210 individually or in an array. The layers 210 may all be formed of the same material or may be formed of different materials. The etching may be carried out in a single step or in a series of steps to achieve the multiple depths required. Alternative processes such as laser ablation, micromachining, or other known processes may also be used. Once the plurality of layers 210 have been formed, they are assembled with the non-etched outer layers 220 and joined by diffusion bonding. Again, alternative techniques such as conventional bonding with adhesives, welding, or similar processes may also be used as is known in the art. The resulting stack of layers 210, 220 is joined, sealing the flow passages 270 and forming the flow restrictor 160. Subsequent finishing steps can be performed to alter the overall shape or size of the flow restrictor 160 to suit the dimensions of the flow passages into which the flow restrictor 160 is installed. These processes may include grinding, machining, laser cutting, water jetting, or other known techniques. Indeed, the flow restrictor 160 does not need to remain rectangular and may be formed into cylindrical shapes as will be discussed further below.

[0069] Turning to Figs. 10-16, a second embodiment of the flow restrictor 300 is best shown in Fig. 10. Where not explicitly noted, the reference numerals are identical to those of the first embodiment of the flow restrictor 160. The second embodiment of the flow restrictor 300 extends from a first end 302 to a second end 303 along a longitudinal axis A-A and is also formed of a plurality of layers 310 having flow passages and a plurality of outer layers 320 which do not have flow passages. After bonding, the layers 310, 320 are post-processed into a cylindrical shape which facilitates insertion into a cylindrical bore, enabling easy installation of the flow restrictor 300 into a valve or other flow device.

[0070] As shown in Fig. 11, a selection of the layers 310 are shown in perspective. The layers 310 extend from a first end 313 to a second end 314 opposite the first end 313. Figs. 12A and 12B best illustrate the apertures 312 formed into the first end 313 of the layers 310. As can also be seen, the layers 310 comprise two first layers 330 and two second layers 360. As best seen in Fig. 12B, the apertures 312 have a first edge 315, a second edge 316 opposite the first edge 315, a third edge 317, and a fourth edge 318 opposite the third edge 317. The first and second edges 315, 316 are formed by the first layers 330. The third and fourth edges 317, 318 are each formed by the second layer 360.

[0071] An exploded view of the layers 310 is shown in Fig. 13, better illustrating the flow passages of the restrictor 300. Figs. 15 and 16 illustrate the first layer 330 and the second layer 360, respectively. The first layer 330 has a first side 331, a second side 332, a third side 333, a fourth side 334, a front face 335, and an opposite rear face 336. The second layer 360 has a first side 361, a second side 362, a third side 363, a fourth side 364, a front face 365, and an opposite rear face 366. The first layer 330 has a series of longitudinal passages 339 that terminate in layer transition apertures 340. The longitudinal passages 339 and the layer transition apertures 340 extend through the entirety of the first layer 330. The second layer 360 has notches 369 that extend from the first and second sides 361, 362. The notches 369 also extend through the entirety of the second layer 360. As can be best seen in Fig. 14, the apertures 312 are formed by the open ends of the notches 369 when the layers 330, 360 are alternately stacked as shown. Flow passages 370 are formed by the stacking of the layers 330, 360 as shown. In alternate embodiments, the layer transition apertures may be formed in a variety of shapes and may be formed with or without flow passage contouring at the ends of the channel, or with contouring of different shapes.

[0072] Once again, a plurality of the layers 330, 360 are stacked and assembled with the outer layers 320. The layers are then bonded through diffusion bonding or a similar technique. The resulting resistor stack is then ground or machined into a cylindrical shape as shown in Fig. 10. This cylindrical shape also incorporates annular grooves which facilitate the mounting of a seal which seals the flow restrictor 300 into a bore of a device to ensure that the only gas passing by the flow restrictor 300 must pass through the passages 370. In other embodiments, the final part may be machined into different shapes, or alternatively left in its raw shape formed by the bonded resistor stack.

[0073] A third embodiment of the flow restrictor 400 is shown in Figs. 17-22. Fig. 17 shows a selection of the plurality of layers 410 forming the flow passages of the flow restrictor 400. The outer layers are not shown in this embodiment as they are substantially identical to those of the other embodiments. The plurality of layers 410 extend from a first end 413 to a second end 414 opposite the first end 413. As best shown in Fig. 18, apertures 412 are formed in the first end 413 and the second end 414 to permit passage of gas into and out of the flow restrictor 400. Fig. 19 shows an exploded view of the plurality of layers 410 to better illustrate the flow passages. As can be seen, the plurality of layers 410 comprise two first layers 430 and two second layers 460.

[0074] Figs. 21 and 22 illustrate the first layer 430 and the second layer 460, respectively. The first layer 430 has a first side 431, a second side 432, a third side 433, a fourth side 434, a front face 435, and an opposite rear face 436. The second layer 460 has a first side 461, a second side 462, a third side 463, a fourth side 464, a front face 465, and an opposite rear face 466. The first layer 430 has a series of longitudinal passages 439 having an elongated configuration with straight sides and a radius at each end. The second layer 460 has notches 469 that transition from a u-shape having parallel sides to angled sides which increase in width as they approach the first side 461 or second side 462 of the second layer 460. The notches 469 overlap with the longitudinal passages 439 when the first and second layers are aligned. The second layer 460 also has D-shaped apertures 468 which allow the connection of two adjacent longitudinal passages 439 to increase the effective length of the flow passage from one aperture 412 to another aperture 412. There is no limit to the number of D-shaped apertures 468 which may be employed. Furthermore, there is no need to limit the apertures 468 to a D shape, and they may be any desired shape to facilitate a connection between adjacent longitudinal passages 439. In alternate embodiments the notches 469 can be shaped differently. For instance, shapes such as

rectangular, wedge, or other shapes may be used. Additionally, longitudinal passages 439 can have contouring in them to improve flow characteristics. Thus, the longitudinal passages 439 need not be formed with a constant width, and may have varying widths at either ends or anywhere along their length. In yet further embodiments a third layer (or a plurality of layers) can be interleaved between the first layer 430 and the second layer 460 such that each first layer 430 only contacts one second layer 460, and the apertures 468 between subsequent sheets do not allow flow transitions except for adjacent first and second layers 430, 460.

[0075] As can be best seen in Fig. 20, the apertures 412 are formed by the open ends of the notches 469 when the layers 430, 460 are alternately stacked as shown. Flow passages 470 are formed by the stacking of the layers 430, 460 as shown. The layers 430, 460 are of equal thickness in this embodiment, but may have different thicknesses if desired.

[0076] A fourth embodiment of the flow restrictor 500 is shown in Figs. 23-29. Fig. 23 shows a selection of the plurality of layers 510 forming the flow passages of the flow restrictor 500. The outer layers are not shown in this embodiment as they are substantially identical to those of the other embodiments. The plurality of layers 510 extend from a first end 513 to a second end 514 opposite the first end 513. As best shown in Fig. 24, apertures 512 are formed in the first end 513 and the second end 514 to permit passage of gas into and out of the flow restrictor 500. Fig. 25 shows an exploded view of the plurality of layers 510 to better illustrate the flow passages. As can be seen, the plurality of layers 510 comprise a first layer 530, a second layer 560, and a third layer 580.

[0077] Figs. 27-29 illustrate the first layer 530, the second layer 560, and the third layer 580, respectively. The first layer 530 has a first side 531, a second side 532, a third side 533, a fourth side 534, a front face 535, and an opposite rear face 536. The second layer 560 has a first side 561, a second side 562, a third side 563, a fourth side 564, a front face 565, and an opposite rear face 566. The first layer 530 has a series of longitudinal passages 539 having an elongate configuration with straight sides and a radius at each end. The second layer 560 has notches 569 that transition from a u-shape having parallel sides to angled sides which increase in width as they approach the first side 561 or second side 562 of the second layer 560. The notches 569 overlap with the longitudinal passages 539 when the first and second layers are aligned. The third layer 580 has a first side 581, a second side 582, a third side 583, a fourth side 584, a front face 585, and an opposite rear face 586. As can be best seen in Fig. 26, the apertures 512 are formed by the open ends of the notches 569 when the layers 530, 560 are alternately stacked as

shown. Flow passages 570 are formed by the stacking of the layers 530, 560 as shown. The layers 530, 560 are of equal thickness in this embodiment, but may have different thicknesses if desired. The third layer may be useful for decreasing the density of the flow passages, ensuring that flow is more evenly distributed across the cross-sectional area of the flow restrictor 500. This is particularly useful for producing very high flow impedance flow restrictors.

[0078] A fifth embodiment of the flow restrictor 600 is shown in Figs. 30-36. Fig. 30 shows the flow restrictor 600 in perspective. The flow restrictor 600 extends from a first end 602 to a second end 603 and has outer layers 620 which surround layers 610 which have flow passages therein. A selection of the layers 610 are shown in Fig. 31 in perspective view. These layers 610 extend from a first end 613 to a second end 614, with apertures 612 on the first and second ends 613, 614. An exploded view of the layers 610 is shown in Fig. 33, illustrating two first layers 630 and two second layers 660.

[0079] The first layer 630 and the second layer 660 are illustrated in Figs. 35 and 36. The first layer 630 has a first side 631, a second side 632, a third side 633, a fourth side 634, a front face 635, and an opposite rear face 636. The second layer 660 has a first side 661, a second side 662, a third side 663, a fourth side 664, a front face 665, and an opposite rear face 666. The first layer 630 has a series of longitudinal passages 639 having an elongated configuration which meet with U shaped portions 640 or with openings 641. The second layer 660 is free of any flow passages or other features. As can be seen, in the flow restrictor 600, gas remains exclusively on a single layer 630 and does not transition between first and second layers 630, 660. Instead, it enters through an opening 641 at the first side 631, travels down a longitudinal passage 639, returns along a U shaped portion 640 at least two times, then exits through an opening 641 on the second side 632. The exact flow path may be altered to zig-zag, utilize more than two U shaped portions 640, no U shaped portions 640, or take any other path on the layer 630. However, it never flows through the second layer 660 in this embodiment. The longitudinal passages 369, U shaped portions 640, and openings 641 all extend through the entirety of the thickness of the first layer 630. In alternate configurations, single sheet flow may be obtained by forming the flow passage depth only partially through the sheet such that the sheet dimensions remain intact during assembly prior to bonding.

[0080] As best shown in Fig. 34, flow passages 670 are formed by the stacking of the layers 630, 660 as shown. The layers 630, 660 are of equal thickness in this embodiment, but may have different thicknesses if desired. The layers 630, 660 are formed individually of different

materials having a different reactivity when subjected to etching chemicals. The material of the first layer 630 may be more reactive than the material of the second layer 660, facilitating effective etching of the first layer 630 without significant etching of the second layer 660. Layer pairs are formed by assembling one first layer 630 with one second layer 660. The layer pairs are then diffusion bonded so they cannot be readily separated. As discussed above, other bonding techniques may be utilized. Then, the layer pairs are etched so that the flow passages 670 are formed into the first layer 630 without etching the second layer 660. The layer pairs are then assembled into the plurality of layers 610 having flow passages 670. Outer layers 620 are also assembled with the plurality of layers 610 having the flow passages 670. Finally, the layers 610, 620 are diffusion bonded together. Optionally, post processing such as grinding may be used to form the flow restrictor 600 and adapt it for installation into a flow passage of a device.

[0081] It should be noted that the flow passages do not need to extend straight from one end of the flow restrictor to the other end of the flow restrictor, or double back in parallel rows. Instead, it is conceived that the flow passages may zig-zag, arc, or take any other path needed to achieve the desired flow impedance in the completed flow restrictor. Multiple layer transitions may also be made, enabling the use of flow passages which fork and rejoin, transition across more than two or three layers, or the like. It is further conceived that flow restrictors may incorporate features of specific embodiments in combination, such that a hybrid of the disclosed embodiments may be constructed. The above-disclosed restrictor designs can be used to achieve highly laminar flow and high part to part reproducibility. This high reproducibility reduces calibration requirements when manufacturing flow control devices utilizing one or more laminar flow elements.

[0082] Details illustrating a method of forming the flow restrictors according to the present invention are shown in Figs. 37-41. Fig. 37 shows a plurality of layer blanks 710 in an exploded view. Each of the layer blanks has a first edge 711, a second edge 712 opposite the first edge, a third edge 713, and a fourth edge 714 opposite the third edge. The layer blanks 710 further comprise a front face 715 and a rear face 716 opposite the front face 715. The layer blanks 710 are formed into first layers 730 and second layers 760 as further illustrated in Figs. 38 and 39. The first layer 730 is modified from a layer blank 710 by forming a second cavity 732 into the first layer 730. The second layer 760 is modified from a layer blank 710 by forming a first cavity 761 and a third cavity 763 into the second layer 760. The first, second, and third cavities 761, 732, 763 are formed into the front faces 715 of their respective first and second layers 730,

760. Preferably the cavities 761, 732, 763 are formed through the thickness of the layers 730, 760. In some embodiments, some or all of the cavities 761, 732, 763 may be formed only partially through the thickness of the layers 730, 760. In the illustrated method, the cavities 761, 732, 763 are formed from the front face 715 to the rear face 716. The cavities 761, 732, 763 are spaced from the first, second, third, and fourth edges 711, 712, 713, 714 of the layer blanks 710.

[0083] The cavities 761, 732, 763 are formed by etching the layer blanks 710. Alternate processes are available such as micromachining, laser ablation, or other known techniques. As illustrated in Fig. 40, a resistor stack 770 is formed from the plurality of layers 730, 760. Subsequent to formation of the cavities 761, 732, 763, the layers 730, 760 are stacked in alternating layers, ensuring that the layers 730, 760 are kept in alignment so that the second cavity 762 overlaps with the first and third cavities 761, 763. The layers 730, 760 are then bonded to form the resistor stack 770 as a unitary component. The layers 730, 760 may be bonded by diffusion bonding, welding, gluing, or any other known technique.

[0084] The resistor stack 770 comprises a first unfinished end 771 formed by the first edges 711 of the first and second layers 730, 760. An opposite second unfinished end 772 is formed by the second edges 712 of the first and second layers 730, 760 of the resistor stack 770. As can be seen, no cavities are exposed on the unfinished ends 771, 772. In alternate embodiments, only one of the layers 730, 760 need have cavities, with the other layers 730, 760 being free of cavities. This allows formation of resistors such as those shown in Figs. 30-36. In yet other embodiments, three or more different types of layers may be utilized such as is shown in Figs. 23-27. The layers need not be alternately stacked, but instead may simply be separated from each other. Thus, un-modified layer blanks 710 may be interleaved with the first and second layers if so desired. Any combination of layers can be made so long as at least one flow passage is formed in the finished flow resistor.

[0085] Fig. 41 illustrates the resistor stack 770 after finishing operations have been completed. These finishing operations can take one of two alternative forms. In the first process, the unfinished ends 771, 772 are broken off of the resistor stack 770 to expose the first and third cavities 761, 763. The exposed first and third cavities 761, 763 form apertures 712 on first and second finished ends 773, 774. This results in flow passages extending from the apertures 712 on the first finished end 773 to the apertures 712 on the second finished end. Optionally, additional material removal operations can be done to the resistor stack 770 prior to removal of the unfinished ends 771, 772. This has the benefit of minimizing the amount of debris which

enters the flow passages, ensuring that the resulting flow restriction closely matches the theoretical flow restriction provided by the flow restrictor. Furthermore, manufacturing repeatability is greatly improved by ensuring that debris cannot enter the flow passages.

[0086] In an alternative second process, the unfinished ends 771, 772 of the resistor stack 770 are removed through conventional material removal processes such as machining, milling turning, sawing, grinding, electrical discharge machining, or etching. Once the unfinished ends 771, 772 are removed to form the finished ends 773, 774, the resistor stack 770 is rinsed with deionized water. An electropolish process is used to dissolve any remaining metal particles and produce a surface having very low roughness. Next, deionized water is pumped through the flow passages to flush the electropolishing solution. The resistor stack 770 is then dried and subsequently a nitric acid solution is used to remove any remaining free iron, phosphates, and sulfates. This results in a surface which is extremely clean and free of contaminants.

[0087] While the invention has been described with respect to specific examples including presently preferred modes of carrying out the invention, those skilled in the art will appreciate that there are numerous variations and permutations of the above described systems and techniques. It is to be understood that other embodiments may be utilized, and structural and functional modifications may be made without departing from the scope of the present invention. Thus, the spirit and scope of the invention should be construed broadly as set forth in the appended claims.

CLAIMS

1. A method of manufacturing a flow restrictor, the method comprising:

a) providing a plurality of layer blanks, the layer blanks having a first edge, a second edge opposite the first edge, a third edge, a fourth edge opposite the third edge, a front face, and a rear face opposite the front face;

b) forming a first cavity in the front face of a first one of the plurality of layer blanks;

c) stacking the plurality of layer blanks;

d) bonding the plurality of layer blanks to form a resistor stack having a first unfinished end and an opposite second unfinished end, the first unfinished end of the resistor stack formed by the first edges of the plurality of layer blanks and the second unfinished end of the resistor stack formed by the second edges of the plurality of layer blanks;

e) removing material from the first unfinished end of the layer stack to expose the first cavity and form a first aperture.

2. The method of claim 1 wherein step b) further comprises forming a second cavity in the front face of a second one of the plurality of layer blanks, the second cavity fluidly connected to the first cavity.

3. The method of claim 2 wherein step b) further comprises forming a third cavity in the front face of the first one of the plurality of layer blanks.

4. The method of claim 3 wherein step e) further comprises removing material from the second unfinished end of the resistor stack to expose the third cavity and form a second aperture.

5. The method of claim 1 wherein the first cavity formed in step b) is spaced from each of the first, second, third, and fourth edges of the layer blank.

6. The method of claim 1 wherein step e) further comprises breaking off the first unfinished end of the resistor stack.

7. The method of claim 1 wherein step e) further comprises machining the first unfinished end of the resistor stack.

8. The method of claim 1 further comprising step f), step f) comprising rinsing the resistor stack with deionized water.

9. The method of claim 8 further comprising step f-1) subsequent to step f), step f-1) comprising electropolishing the resistor stack.

10. The method of claim 9 further comprising step f-2) subsequent to step f-1), step f-2) comprising rinsing the resistor stack with deionized water.

11. The method of claim 10 further comprising step f-3) subsequent to step f-2), step f-3) comprising treating the resistor stack with nitric acid.

12. A method of manufacturing a flow restrictor, the method comprising:

a) providing a plurality of layer blanks, the layer blanks having a first edge, a second edge opposite the first edge, a third edge, a fourth edge opposite the third edge, a front face, and a rear face opposite the front face;

b) forming a first cavity extending through a first one of the plurality of layer blanks from a front face to an opposite rear face;

c) stacking the plurality of layer blanks;

d) bonding the plurality of layer blanks to form a resistor stack having a first unfinished end and an opposite second unfinished end, the first unfinished end of the resistor stack formed by the first edges of the plurality of layer blanks and the second unfinished end of the resistor stack formed by the second edges of the plurality of layer blanks;

e) removing material from the first unfinished end of the layer stack to expose the first cavity and form a first aperture.

13. The method of claim 12 wherein step e) further comprises removing material from the second unfinished end of the restrictor stack to expose the first cavity and form a second aperture.

14. The method of claim 12 wherein the first one of the plurality of layer blanks comprises a second cavity extending from the front face to the opposite rear face.

15. The method of claim 14 wherein the second cavity is isolated from the first cavity.

16. The method of claim 14 wherein, in step e), the step of removing material also exposes the second cavity to form a third aperture.

17. The method of claim 12 further comprising step f), step f) comprising rinsing the resistor stack with deionized water.

18. The method of claim 17 further comprising step f-1) subsequent to step f), step f-1) comprising electropolishing the resistor stack.

19. The method of claim 18 further comprising step f-2) subsequent to step f-1), step f-2) comprising rinsing the resistor stack with deionized water.

20. The method of claim 19 further comprising step f-3) subsequent to step f-2), step f-3) comprising treating the resistor stack with nitric acid.