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Vapor cells and related systems and methods

Abstract

Vapor cells may include a body including a cavity within the body. A first substrate bonded to a second substrate at an interface within the body, at least one of the first substrate, the second substrate, or an interfacial material between the first and second substrates may define at least one recess or pore in a surface. A smallest dimension of the at least one recess or pore may be about 500 microns or less, as measured in a direction parallel to at least one surface of the first substrate partially defining the cavity.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS (1) This application is a continuation of U.S. patent application Ser. No. 17/678,655, filed Feb. 23, 2022, now U.S. Pat. No. 11,764,796, issued Sep. 19, 2023, which claims the benefit under 35 U.S.C. § 119(e) of the priority date of U.S. Provisional Patent Application Ser. No. 63/263,897, filed Nov. 11, 2021, for EMPLOYING PORES FOR CONTROLLING VAPOR PRESSURE IN VAPOR CELLS, AND RELATED VAPOR CELLS, SYSTEMS, AND METHODS, the disclosure of each of which is incorporated herein in its entirety by this reference.

FIELD

(1) This disclosure relates generally to techniques for controlling vapor pressure of subject materials in vapor cells for atomic clocks and other applications. More specifically, disclosed examples relate to structures and materials for controlling vapor pressure, which may improve reliability of operation across broader temperature ranges.

BACKGROUND

(2) Vapor pressure at a liquid-vapor interface is affected by surface tension according to the Kelvin equation:

$$(3) \frac{P}{P_{\text{sat}}} = e^{-\frac{\gamma V_m}{rRT}},$$

where P/P_{sat} is the ratio of the vapor pressure to the saturated vapor pressure, γ is the surface tension, $V_{\text{sub.m}}$ is the molar volume of the liquid, r is the radius of the droplet or meniscus, R is the universal gas constant, and T is the absolute temperature. Vapor pressure is relevant in a variety of operational contexts, including, without limitation, atomic clocks.

BRIEF SUMMARY

(4) In some examples, vapor cells may include a body defining a cavity within the body. A first substrate may be bonded to a second substrate at an interface. At least one of the first substrate, the second substrate, or an interfacial material between the first substrate and the second substrate may define at least one recess or pore. The at least one recess or pore may have a smallest dimension of about 500 microns or less, as measured in a direction parallel to at least one surface of the first substrate partially defining the cavity.

(5) In other examples, methods of using vapor cells may involve providing a vapor cell including a body. The body may include a first substrate bonded to a second substrate at an interface. A cavity may be defined within the body. At least one pore or recess may be formed in at least one of the first substrate, the second substrate, or an interfacial material between the first substrate and the

second substrate. The at least one pore or recess may have a smallest dimension of about 500 microns or less, as measured in a direction parallel to at least one surface of the first substrate partially defining the cavity.

(6) In other embodiments, a system may include an emitter positioned and oriented to direct radiation through windows of a vapor cell. The system may include a detector positioned and oriented to detect the radiation. The vapor cell may include a body defining a cavity within the body. The body may include a first substrate, a second substrate, or an interfacial material between the first substrate and the second substrate. The first substrate, the second substrate, or the interfacial material between the first substrate and the second substrate may define at least one pore or recess having a smallest dimension of about 500 microns or less, as measured in a direction parallel to at least one surface of the first substrate partially defining the cavity.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

(1) While this disclosure concludes with claims particularly pointing out and distinctly claiming specific embodiments, various features and advantages of embodiments within the scope of this disclosure may be more readily ascertained from the following description when read in conjunction with the accompanying drawings. In the drawings:

(2) FIGS. 1A and 1B are schematic cross-sectional side views of examples of vapor cells;

(3) FIGS. 2A, 2B, 2C, and 2D are schematic cross-sectional side views of other examples of vapor cells;

(4) FIGS. 3A and 3B are flowcharts depicting illustrative methods of making a vapor cell; and

(5) FIGS. 4A and 4B are schematics of illustrative systems including a vapor cell in accordance with this disclosure.

DETAILED DESCRIPTION

(6) Disclosed examples relate generally to designs for structural features that allow for control of vapor pressure in vapor cells for, as a nonlimiting example, atomic clocks. Such designs and structural features may, as a nonlimiting example, increase the temperature range over which reliable operation may be achieved. More specifically, disclosed examples relate to structures and methods for forming recesses and or pores in vapor cells for controlling (e.g., suppressing) vapor pressure. For example, at least one surface in a vapor cell may include one or more recesses or pores sized, shaped, positioned, and configured to control (e.g., suppress) vapor pressure of a subject material in the vapor cell. The recess or recesses may be formed by, for example, selectively etching certain material of a stacked structure of a portion of a body of the vapor cell, thereby recessing certain portions of the stacked structure relative to other portions of the stacked structure to form one or more recesses. As another illustrative technique for forming the pore or pores, a material of a portion of a substrate, or the material of portions of multiple substrates in a stacked structure forming a portion of a body of the vapor cell, may be rendered porous, and certain portions of the porous material and of any relevant non-porous material may be removed to form a portion of a cavity of the vapor cell, and the substrate or substrates may be oriented, stacked, and bonded to one another to form at least a portion of the body of the vapor cell with the porous material exposed to, and placed in a predetermined location relative to, the cavity. Disclosed methods of controlling vapor pressure may provide volumes of capillaries for holding subject material in a liquid state therein and for inducing an exposed surface of the subject material in the liquid state to be concave.

(7) As used herein, the terms “substantially” and “about” in reference to a given parameter, property, or condition means and includes to a degree that one of ordinary skill in the art would understand that the given parameter, property, or condition is met with a degree of variance, such as

within acceptable manufacturing tolerances. For example, a parameter that is substantially or about a specified value may be at least about 90% the specified value, at least about 95% the specified value, at least about 99% the specified value, or even at least about 99.9% the specified value.

(8) The term “pore,” as used herein, means and includes surface features having an average dimension less than 500 microns, as measured in at least one direction parallel to a major surface defining a cavity to which the pore is exposed. For example, “pores” include interconnected, three-dimensional networks of voids within a material that may be occupied by environmental fluids (e.g., air, inert gas, subject material). “Pores” also include, for example, depressions, divots, dimples, and other surface features having average dimensions less than 500 microns, which may be measurable as surface roughness.

(9) The term “interface” as used herein, means and includes a point or region of attachment between two materials or structures. For example, an “interface” may include direct contact between two adjacent surfaces, or may include an interfacial material interposed between, and attaching, two adjacent surfaces on opposite sides of the interfacial material.

(10) Unless the context indicates otherwise, removal of materials or surface modifications described herein may be accomplished by any suitable technique including, but not limited to, etching (e.g., dry etching, wet etching, vapor etching, reactive ion etching, stain etching), ion milling, abrasive planarization (e.g., chemical-mechanical planarization (CMP)), anodization, or other known methods.

(11) The upper operating temperature limit of vapor-cell atomic clocks, such as chip scale atomic clocks (CSACs), without limitation, may be limited by excessive optical absorption, collisional line broadening, and/or heating of a trapped sample due to the high density of alkali metal vapor at elevated temperatures. The vapor pressure above a liquid may be suppressed by containing the liquid within a recess, recesses, pore, or pores. Such structures may enable depressing the alkali metal vapor pressure. In accordance with the Kelvin equation mentioned above, if the curvature of a droplet of subject liquid is convex, $r > 0$, then $P > P_{\text{sub.sat}}$. If the curvature is concave, $r < 0$, then $P < P_{\text{sub.sat}}$. Maintaining control over the vapor pressure of the metal vapor requires the holding capacity (e.g., volume) of the pores to be equal to or greater than a volume required to hold a mass of the metal vapor in a liquid or solid state.

(12) Reducing subject material vapor pressure within vapor cells of atomic clocks may be achieved by introducing at least one recess or pore that affects the surface shape of masses of the subject material in the pores. Stated another way, the interaction between the subject material and the size and shape of a pore causes a shape of a surface of the subject material to change in a desired manner (introduces a disturbance) as compared to a shape of the surface of the subject material when on a generally flat surface.

(13) When forming vapor cells, top and bottom windows may be bonded to opposite surfaces of a remainder of a body of the vapor cell having cavities formed in the remainder, each cavity corresponding to a respective vapor cell to be singulated from a wafer. The cavities may be formed, by way of example, by etching or micromachining through a material of the remainder of the body of the vapor cell (e.g., a substrate, a wafer, a stacked structure). By way of example, the geometry of a cylindrical cavity may be described by height and diameter, wherein the height of the cavity may be defined as the distance from the at least one window to another window located at an opposite side of the cavity, and the diameter of the cavity may be defined as the distance between sidewalls defining the cavity, as measured in a direction perpendicular to the sidewalls and along a line intersecting a central geometric axis of the cavity. The height and diameter of the cavity may be used to describe geometric differences along the sidewalls of the cavity of the vapor cell. In other examples, the cavity may have a shape other than cylindrical (e.g., ovoid, rectangular prism, rectangular prism having one or more rounded and/or chamfered edges and/or corners). A subject material may be introduced into the cavity of each vapor cell, and the cavities may be enclosed to contain the subject material. For example, each cavity may be enclosed using anodic bonding to

bond the top and bottom windows to major surfaces of the remainder of a body of the vapor cell. In embodiments where the body of the vapor cell comprises a wafer or stacked wafers, individual vapor cells may be diced from the wafer or stacked wafers.

(14) In one or more examples, surface modification may include generation of one or more recesses in the walls of a body of a vapor cell, with the recesses partially defining a cavity of the vapor cell. By way of example, a recess may be formed by bonding two wafers or substrate with an interfacial material therebetween and subsequently removing a portion of the interfacial material to form a recess cooperatively defined by the adjacent substrates and the interfacial material. As a specific example, an oxide layer may be grown on a first silicon wafer, and a second silicon wafer may be surface bonded to the first silicon wafer with the oxide layer therebetween. Holes to define sidewalls of the vapor cell cavities may be formed through the first and second wafers and the oxide layer, either before or after bonding, by, for example, masking and etching, drilling, selectively growing the oxide layer only on those portions of the wafers that will not be removed to form the cavities, or performing any combination of these. The recess may then be formed by selectively etching the oxide layer, forming a recess with a depth controlled by the time of exposure to the etchant material (e.g., HF etching) and a height controlled by the growth of the oxide layer. In some examples, the body of the vapor cell may include more than two bonded substrates, such as, for example, by stacking three or more wafers bonded together with an interfacial material between each pair of wafers, and a series of recesses, one for each interfacial material.

(15) By way of additional example, recesses may be formed by providing a substrate or wafer with alternating regions of oxide material between regions of non-oxide material, the oxide material being recessed relative to the non-oxide material to form a recess. This may be accomplished by, for example, alternately growing the oxide and non-oxide materials on a wafer. For example, silicon oxide may be alternately grown with silicon nitride or polysilicon materials on a silicon wafer through epitaxy, providing selective control of the height of the pores to be formed by partial removal of the regions of oxide material. Two at least substantially complementary wafers or substrates having the alternating regions of oxide and non-oxide materials facing one another may be bonded to one another by surface bonding techniques. Cavities may be formed by, for example, drilling and/or etching the wafers or substrates and the alternating regions of oxide and non-oxide materials. Recesses in the cavities may be formed utilizing, for example, a selective etch (e.g., HF etch) to remove portions of the oxide material while leaving the non-oxide material, providing selective control over the depth of the recesses. Recesses, as disclosed herein, may also be characterized as “trenches.”

(16) FIGS. 1A and 1B are schematic cross-sectional side views of examples of vapor cells **100**. Each vapor cell **100** may include, for example, a body **105** which contains a cavity **110**. For example, the body **105** may include windows **115** forming one or more walls (e.g., boundaries) of the body **105**, with the remaining sidewalls **120** being opaque. More specifically, the windows **115** may include, for example, a transparent or translucent borosilicate or aluminosilicate glass material, enabling the cavity **110** of the vapor cell **100** to be viewable through each of the windows **115**.

(17) The body **105** defining the cavity **110** within the body **105** may include a first substrate **155** bonded to a second substrate **160** at an interface, which may be defined by an interfacial material **130** interposed between the first substrate **155** and the second substrate **160**. At least one of the first substrate **155**, the second substrate **160**, or the interfacial material **130** may define at least one recess **145** having a smallest dimension of 500 microns or less. For example, a surface of the interfacial material **130** facing the cavity **110** may be recessed relative to surfaces of the first substrate **155** and the second substrate **160** facing the cavity **110**, such that the first substrate **155**, second substrate **160**, and interfacial material **130** may cooperatively define a recess **145**. The recess **145** may include, for example, an annular recess extending around a circumference of the body **105** and exposed to a remainder of the cavity **110**. The interfacial material **130** may include an

oxide material interposed between, and bonded to, the first substrate **155** and the second substrate **160**. The body **105** may include a stack of substrates including at least the first substrate **155** and the second substrate **160** and a respective mass of the interfacial material **130** interposed between each pair of substrates of the stack of substrates. For example, the body **105** may include the first substrate **155**, the second substrate **160** adjacent to the first substrate **155**, and a third substrate **165** located on a side of the second substrate **160** opposite the first substrate **155**, with a mass of the interfacial material **130** between the first substrate **155** and the second substrate **160** and another mass of the interfacial material **130** between the second substrate **160** and the third substrate **165**. Each respective mass of the interfacial material **130** may be recessed relative to each pair of adjacent substrates to define a respective recess **145** between each pair of adjacent substrates. Each of the first substrate **155**, the second substrate **160**, and the third substrate **165** may include a substrate material **125**. For example, the substrate material **125** may include a silicon material. (18) The sidewalls **120** of the vapor cell **100** may include a substrate material **125** defined by respective substrates (e.g., the first substrate **155**, the second substrate **160**, the third substrate **165**), and the interfacial material **130**. The sidewalls **120** of the cavity **110** may be configured such that the substrate material **125** and the interfacial material **130** cooperatively form a recess **145**, the surface of the recess **145** inside the cavity **110** being inset relative to the substrate material **125**. The substrate material **125** and interfacial material **130** may be formed of, and include, at least one material with specific properties to facilitate chemical processing (e.g., etching). The substrate material **125** may, for example, be selectively etch resistant in comparison to the interfacial material **130** during contemporaneous exposure to an etchant (e.g., hydrofluoric acid (HF)). By way of example only, the substrate material **125** may be selected to include single crystal or polycrystalline silicon or silicon nitride, and the interfacial material **130** may be selected to include silicon oxide. The characteristics of the recesses **145**, including but not limited to number, size, shape, height, depth, and lateral circumference of the recesses **145**, may be configured to induce the vapor pressure of a subject material **140** in the cavity **110** to be within predetermined thresholds in anticipated operating conditions for the vapor cell **100**. The height of the recesses **145** may be defined as the distance along the sidewall **120** that a recess **145** occupies. By way of example, the height of the recesses **145** may be substantially the same as the thickness of interfacial material **130**. The depth of the recesses **145** may be defined as the distance the recess **145** is offset relative to the inner cavity **110** surface. By way of example, the depth of the recesses **145** may be substantially the same as the distance between surface of the substrate material **125** facing the cavity **110** and surface of the interfacial material **130** facing the cavity **110**. By way of example, the height of a given recess **145** may be between about 20 nm and about 500 nm, and the depth of the recess **145** may be between about 10 μm and about 100 μm . By way of example, the recesses **145** may be sized, shaped, positioned, and configured to contain between about 0.01 μg and about 100 μg of a subject material **140**. More specifically, the volume of the recesses **145** may be sized, shaped, positioned, and configured to contain between about 0.25 μg and about 5 μg of a subject material **140**.

(19) Regarding FIG. 1A, the interfacial material **130** may be selected such that it may be grown directly on the surface of a wafer or substrate of substrate material **125**. By way of example, the interfacial material **130** (e.g., silicon oxide), may result from modification of the substrate surface (e.g., thermal oxidation) or may be controllably grown on the substrate material **125** (e.g., a silicon wafer, a silicon substrate). Growth of the interfacial material **130** on the substrate material **125** may be accomplished by, for example, a vapor deposition process (e.g., chemical vapor deposition or physical vapor deposition). The sidewalls **120** forming the cavity **110** of the vapor cell may be prepared by stacking wafers or substrates on top of one another and bonding the wafers or substrates to one another, with interfacial material **130** between at least some of the wafers or substrates. As a specific, nonlimiting example, the substrate material **125** and interfacial material **130** may be bonded together by means of a contact and anneal bonding process. The sidewall **120**

may then include the substrate material **125** and the interfacial material **130**, with the interfacial material **130** at least substantially flush with the substrate material **125**. The height of the sidewall **120** may include the combination of the height of the substrate material **125** and the height of the interfacial material **130**. By way of example, three substrates or wafers of the substrate material **125**, each having a respective height of about 500 μm may be utilized. The substrates or wafers of the substrate material **125** may be oxide bonded to each other utilizing the interfacial material **130** (e.g., silicon oxide) as an interfacial material, each instance of the interfacial material **130** having a height of between about 20 nm and about 500 nm. A total height of the stacked structure, including the masses of the substrate material **125** and the masses of the interfacial material **130**, may be, for example, between about 1,000 μm and about 2,000 μm (e.g., about 1,500 μm).

(20) Regarding FIG. **1B**, the body **105** may include alternating regions of disparate materials, such as, for example, the substrate material **125** (e.g., the substrate material **125** of the first substrate **155**, the second substrate **160**, epitaxially grown regions of the substrate material **125** interposed between the first substrate **155** and the second substrate **160**) and the interfacial material **130** interposed between adjacent regions of the substrate material **125**. Each region of the interfacial material **130** may be recessed relative to adjacent regions of the substrate material **125** to define respective recesses **145** between adjacent regions of the substrate material **125**. The first substrate **155** may be interposed between the alternating regions of the substrate material **125** and the interfacial material **130** and a first of the windows **115** on a first side of the body **105**, and a second substrate **160** may be interposed between the alternating regions of the substrate material **125** and the interfacial material **130** and another of the windows **115** on an opposite side of the body **105**. By way of example, the substrate material **125** may include polycrystalline silicon or silicon nitride, and the interfacial material **130** may include silicon oxide. Discrete regions of the substrate material **125** and interfacial material **130** may be, for example, iteratively grown to form portions of the sidewalls **120** of the vapor cell **100**. By way of example, each discrete region of the substrate material **125** may have a height of between about 20 nm and about 500 μm .

(21) Recesses **145** in the form of trenches may be formed in the sidewall **120** by, for example, selectively removing portions of the interfacial material **130** facing the cavity **110** to recess the interfacial material **130** relative to the substrate material **125**. By way of example only, a series of recesses **145** may be provided in the sidewall **120** by chemical etching (e.g., HF) to remove portions of the interfacial material **130**. In some examples, recesses **145** may be formed in the sidewall **120** in such a way as to expose the recesses **145** to the remainder of the cavity **110** by, for example, selectively etching the interfacial material **130**. Each resulting recess **145** may have, for example, an at least substantially annular shape, extending around and in fluid communication with a remainder of the cavity **110**. By way of example only, the interfacial material **130** (e.g., silicon oxide) may be selectively etched using hydrofluoric acid. The cavity **110** of the body **105** of the vapor cell **100** may be enclosed by adding windows **115** covering the open ends of the cavity and bonding the windows **115** to adjacent regions of the substrate material **125**. In embodiments where an array of vapor cells **100** are formed in a wafer, the individual vapor cell **100** may then be singulated from one another, for example, utilizing a dicing saw.

(22) A transparency of the material of the windows **115** may be, for example, about 10% or more within wavelengths of radiation to be directed toward the cavity **110**. More specifically, the transparency of the material of the windows **115** may be, for example, between about 10% and about 99%. As a specific, nonlimiting example, the transparency of the material of the windows **115** may be, for example, between about 20% and about 95% (e.g., about 25%, about 50%, about 75%).

(23) In one or more examples, a pore or recess may be introduced into a vapor cell **100** through modification of a material defining the interior vapor cell **100** wall surface. More specifically, a region of at least one of a first substrate or a second substrate partially defining the cavity may include a porous material defining the pore or pores. When a material of a wafer or substrate

includes silicon, the silicon material may be rendered porous by, for example, anodization, stain etching, bottom-up synthesis, or other techniques for rendering silicon porous. The regions of the wafer or substrate rendered porous may have a diameter larger or smaller than a diameter of the cavities to be formed or partially formed in the wafer or substrate. Material within the regions of the wafer or substrate rendered porous may be removed (e.g., by drilling, by etching), leaving an annular shaped region of the porous material around each partial cavity formed in the wafer or substrate. The wafer may be bonded to another wafer, before or after formation of the cavities, with the porous region or regions in a specified position and orientation to expose pores to the cavities.

(24) For example, a substrate including the porous regions may be interposed between, and bonded to, two other substrates to form a body with the porous material spaced from the windows by the two other substrates. In some such examples, the porous region may be located proximate to the interface between the first substrate and the second substrate. In some examples, a diameter of the cavity proximate to the region of the porous material may be less than a diameter of the cavity distal from the region of the porous material in order to expose pores on the exposed surfaces normal to the principal axis of the cell. For example, the porous material may be located adjacent or proximate to a window of the vapor cell, and transmission of incident radiation through the window may enable application of incident radiation to the subject material with the cavity, despite a restricted aperture for radiation passing through the window to proceed into the cavity due to the narrower diameter of the substrate having the porous material adjacent or proximate to the window.

(25) FIGS. 2A through 2D are schematic cross-sectional views of vapor cells **200**. Each vapor cell **200** may include, for example, a body **205** which defines a cavity **210** within the body **205**. For example, the body **205** may include windows **215** forming one or more walls (e.g., boundaries) of the body **205**, with the remaining sidewalls **220** being opaque. More specifically, the windows **215** may include, for example, a transparent or translucent borosilicate or aluminosilicate glass material, enabling the cavity **210** of the vapor cell **200** to be viewable through the windows **215**.

(26) As shown in FIG. 2A, the body **205** may include a first substrate **255** bonded to a second substrate **260** at an interface including an interfacial material **230** interposed between the first substrate **255** and the second substrate **260**. At least one of the first substrate **255**, the second substrate **260**, or the interfacial material **230** between the first substrate **255** and the second substrate **260** may define at least one pore (e.g., a porous volume **235**) with a smallest dimension of 500 microns or less. For example, the substrate material **225** of at least a portion of one of the stacked substrates (e.g., the first substrate **255**, the second substrate **260**, a third substrate **265**) may be porous, and the porous portion of the substrate material **225** may be exposed to the cavity **210**. More specifically, a region of the second substrate **260** proximate a geometric center of the body **205** between the windows **215** may be porous, and the second substrate **260** may be interposed between, and bonded to, the first substrate **255**, at an interface including an interfacial material **230** interposed between the first substrate **255** and the second substrate **260**, and bonded to the third substrate **265** to which the windows **215** are respectively bonded, where the bond to the third substrate **265** is at an interface including an interfacial material **230** interposed between the second substrate **260** and the third substrate **265**. Each of the first substrate **255**, the second substrate **260**, and the third substrate **265** may include, and be defined by, a respective mass of a substrate material **225**.

(27) The sidewalls **220** of the vapor cell **200** may include the substrate material **225**, and an interfacial material **230**. By way of example only, the substrate material **225** may include polycrystalline silicon or silicon nitride, and the interfacial material **230** may include silicon oxide. The sidewalls **220** of the cavity **110** may be configured such that at least a portion of the substrate material **225** may be porous, defining a porous volume **235** exposed to and partially defining the cavity **210**. By way of example, the substrate material **225** may be rendered porous by anodization, stain etching, bottom-up synthesis, or other techniques for rendering silicon porous in examples where the substrate material **225** includes silicon (e.g., silicon nitride, polycrystalline silicon).

Additionally, the interfacial material **230** may also be rendered porous, allowing for the porous volume **235** to be defined in the substrate material **225**, the interfacial material **230**, or both the substrate material **225** and the interfacial material **230**. The characteristics of the porous volume **235**, including but not limited to surface area, volume of pores, shape, and average porous diameter of pores, may be configured to induce the vapor pressure of a subject material **240** in the cavity **210** to be within predetermined thresholds in anticipated operating conditions for the vapor cell **200**. By way of example, the average diameter of pores within the porous volume **235** may be between about 20 nm and about 500 μm . By way of example, the total volume of pores defined by the porous volume **235** may be sized, shaped, positioned, and configured to contain between about 0.01 μg and about 100 μg of a subject material **240**. More specifically, the volume of pores defined by the porous volume **235** may be sized, shaped, positioned, and configured to contain between about 0.25 μg and about 25 μg of a subject material **240**.

(28) Regarding FIG. 2A, as an example embodiment, the sidewall **220** of the vapor cell **200** may include three stacked regions of substrate material **225**, bonded to one another by regions of interfacial material **230** interposed between adjacent regions of the substrate material **225** to facilitate bonding of the substrate material. In other examples, the three stacked regions of substrate material **225** may be directly bonded to one another without interfacial material **230** interposed between adjacent regions of the substrate material **225**. By way of example the substrate material **225** (e.g., the first substrate **255** and the second substrate **260**) may be bonded through direct Si—Si bonding in embodiments where one or more interfaces between adjacent substrates of the body **205** (e.g., between the first substrate **255** and the second substrate **260**, between the second substrate **260** and the third substrate **265**) lacks the interfacial material **230**. By way of example only a middle region of substrate material **225** may include a porous volume **235**, and overlying and underlying regions of the substrate material **225** may be interposed between the porous volume **235** and the respective windows **215**.

(29) Regarding FIG. 2B, as another example, the body **205** may include stacked substrates, such as, for example, a first substrate **255** and a second substrate **260**, bonded to one another at an interface by regions of interfacial material **230** interposed between adjacent regions of the substrate material **225** to facilitate bonding of the substrate material. In another example interfacial material is not provided and first substrate **255** and second substrate **260** are bonded to one another at an interface without interfacial material **230**. At least one of the first substrate **255**, the second substrate **260**, or an interfacial material **230** between the first substrate **255** and the second substrate **260** may define at least one pore having a smallest dimension of 500 microns or less. For example, the first substrate **255**, the second substrate **260**, or both may include a porous volume **235**, a portion of the substrate material **225** of the first substrate **255**, the second substrate **260**, or both being porous. More specifically, the first substrate **255** proximate to one of the windows **215** may include the porous volume **235**, and the porous volume **235** may extend around a circumference of the cavity **210**. As a specific, nonlimiting example, the porous volume **235** may occupy an entirety of the surface of the first substrate **255** exposed to the cavity **210**. In such an example, an entirety of a thickness of the first substrate **255** may be rendered porous utilizing chemical treatment before material is removed from the porous volume **235** to define a portion of the cavity **210**. In some examples, the diameter of the cavity **210** as defined by the first substrate **255** may be smaller than the diameter of the cavity **210** as defined by the second substrate **260**. For example, the first substrate **255** may define a restricted aperture **270** proximate to the window **215** through which radiation may be directed toward the subject material **240** within the cavity **210**. Each of the first substrate **255** and the second substrate **260** may include, and be defined by, a region of substrate material **225**, and a mass of the interfacial material **230** may be interposed between, and bonded to, each adjacent pair of substrates.

(30) The sidewall **220** of the vapor cell **200** may include two stacked regions of substrate material **225**, bonded together with a region of interfacial material **230** interposed between the regions of

substrate material **225**. By way of example only, the two regions of substrate material **225** are displayed as having different heights corresponding to different regions forming different surface areas of the sidewall **220**. For example, the height of the region of substrate material **225** including the porous volume **235** may be less than the height of the other region of substrate material **225** not containing the porous volume **235**. In some examples, the diameter of the cavity **210** may not be constant. By way of example, the diameter of the cavity **210** defined by the region of the substrate material **225** adjacent to the window **215** through which incident radiation is to be received into the cavity **210**, and including the porous volume **235**, may be less than the diameter of the cavity **210** defined by the remainder of the substrate material **225**. Such a configuration may enable the vapor cell **200** to include a larger porous volume **235** without reducing the ability of incident radiation to interact with subject material within the cavity **210**, as beams of radiation may tend to diffuse and expand with distance after passing through the window **215** and beyond the region of substrate material **225** having the smaller diameter.

(31) Regarding FIG. 2C, as another example, the body **205** may include stacked substrates, such as, for example, a first substrate **255** and a second substrate **260**, bonded to one another at an interface. At least one of the first substrate **255**, the second substrate **260**, or an interfacial material **230** between the first substrate **255** and the second substrate **260** may define at least one pore having a smallest dimension of 500 microns or less. For example, the first substrate **255**, the second substrate **260**, or both may include a porous volume **235**, a portion of the substrate material **225** of the first substrate **255**, the second substrate **260**, or both being porous. More specifically, the first substrate **255** proximate to one of the windows **215** may include the porous volume **235**, and the porous volume **235** may extend around a circumference of the cavity **210**. As a specific, nonlimiting example, the porous volume **235** may occupy only a portion of the surface of the first substrate **255** exposed to the cavity **210**, a remainder of the surface of the first substrate **255** exposed to the cavity **210** being nonporous. In such an example, only a portion of a thickness of the first substrate **255** may be rendered porous before material is removed from the porous volume **235** and the remainder of the first substrate **255** to define a portion of the cavity **210**. In some examples, the diameter of the cavity **210** as defined by the first substrate **255** may be smaller than the diameter of the cavity **210** as defined by the second substrate **260**. Each of the first substrate **255** and the second substrate **260** may include a substrate material **225**, and a mass of the interfacial material **230** may be interposed between, and bonded to, each adjacent pair of substrates.

(32) One of the regions of substrate material **225** may include a porous volume **235** occupying only a portion of the surface of the region of substrate material **225** defining the cavity **210**. A remainder of the region of substrate material **225** defining the cavity **210** may be nonporous. For example, the porous volume **235** may be spaced from the window **215**, with the remainder of the region of substrate material **225** interposed between the porous volume **235** and the window **215** being nonporous. The porous volume **235** may also have a depth that is not constant within the region of the substrate material **225**, as measured relative to the surface of the substrate material **225** with the interfacial material **230**. For example, the depth of the porous volume **235** may be greatest proximate to the interfacial material **230** and may decrease nonlinearly as distance from the interfacial material **230** increases. In another example, the depth of the porous volume **235** may be greatest proximate to the interfacial material **230** and may decrease linearly as distance from the interfacial material **230** increases.

(33) The cross sectional profile of the porous volume **235** may be at least partially defined by the method through which it was prepared. By way of example, the selected region for the porous volume **235** may be prepared by creating a patterned hard mask (e.g., silicon carbide) over a surface of the region of substrate material **225**. Exposed portions of the substrate material **225** may be rendered porous by, for example, anodization, stain etching, bottom-up synthesis, or other techniques for rendering silicon porous. With some such techniques, a depth of the porous volume **235** may be at its maximum proximate to the cavity **210**, and may taper to a minimum depth distal

from the cavity **210** (e.g., proximate to the edges of the mask used when rendering the substrate material **225** porous). In some examples, the cross-sectional shape of the porous volume **235** having a non-constant depth may include an at least substantially arcuate portion (e.g., a quarter-circular cross-sectional shape).

(34) In some examples, a porous volume **235** may be rendered into multiple separate substrate material **225** segments. For example, two substrate material **225** segments may be bonded together with an interfacial material **230** interposed between the two substrate material **225** segments. Each substrate material **225** may be rendered to have a region within the cavity to include a respective porous volume **235**. The porous volume **235** may cover the entire surface, or a portion of the surface within the cavity **210** of the substrate material **225**. Such a configuration may provide a concentrated region at which the porous volume **235** is concentrated proximate to, or distal from, the bonding interface.

(35) Regarding FIG. 2D, as another example, the body **205** may include stacked substrates, such as, for example, a first substrate **255** and a second substrate **260**, bonded to one another at an interface. At least one of the first substrate **255**, the second substrate **260**, or an interfacial material **230** between the first substrate **255** and the second substrate **260** may define at least one pore having a smallest dimension of 500 microns or less. For example, the first substrate **255**, the second substrate **260**, or both may include a porous volume **235**, a portion of the substrate material **225** of the first substrate **255**, the second substrate **260**, or both being porous. More specifically, each of the first substrate **255** and the second substrate **260** may include a respective porous volume **235**, and the porous volume **235** may extend around a circumference of the cavity **210**. As a specific, nonlimiting example, a first porous volume **235** may occupy only a portion of the surface of the first substrate **255** exposed to the cavity **210**, a remainder of the surface of the first substrate **255** exposed to the cavity **210** being nonporous, and a second porous volume **235** may occupy only a portion of the surface of the second substrate **260** exposed to the cavity **210**, a remainder of the surface of the second substrate **260** exposed to the cavity **210** being nonporous. In such an example, only a portion of a thickness of the substrate material **225** of the first substrate **255** and the second substrate **260** may be rendered porous before material is removed from the porous volume **235** and the remainder of the first substrate **255** and the second substrate **260** to define a portion of the cavity **210**. The porous volumes **235** may be located, for example, adjacent to the windows **215** on opposite sides of the stacked first substrate **255** and second substrate **260**. As another example, the porous volumes **235** may be located proximate to the interfacial material **230** interposed between, and bonded to, the first substrate **255** and the second substrate **260**. Each of the first substrate **255** and the second substrate **260** may include a substrate material **225**, and a mass of the interfacial material **230** may be interposed between, and bonded to, each adjacent pair of substrates.

(36) Each discrete region of the substrate material **225** may include a respective porous volume **235**. For example, each of the regions of substrate material **225** may include a porous volume **235** occupying only a portion of the surface of the respective region of substrate material **225** defining the cavity **210**. A remainder of the region of substrate material **225** defining the cavity **210** may be nonporous. For example, at least one porous volume **235** may be located proximate (e.g., adjacent) to the window **215**, with the remainder of the region of substrate material **225** interposed between the porous volume **235** and the interfacial material **230** being nonporous. More specifically, each porous volume **235** may be located proximate (e.g., adjacent) to a respective one of the windows **215**, with the remainder of the corresponding region of substrate material **225** interposed between the porous volume **235** and the interfacial material **230** being nonporous.

(37) FIGS. 3A and 3B show a flowchart depicting an illustrative method **300** of making a vapor cell. As specific, nonlimiting examples, the body of the vapor cell may take any of the forms, and may include any of the materials, described previously in connection with FIGS. 1A, 1B, 2A, 2B, 2C, and 2D.

(38) Referring to FIG. 3, the method **300** may involve providing a body, the body including a first

substrate bonded to a second substrate at an interface, as indicated at act **302**. A cavity may be defined within the body, as indicated at act **304**. In at least one of the first substrate, the second substrate, or an interfacial material between the first substrate and the second substrate, at least one pore or recess having a smallest dimension of about 500 microns or less, as measured in a direction parallel to at least one surface of the first substrate partially defining the cavity, may be formed, as indicated at act **306**.

(39) In some examples, forming the at least one pore or recess may involve forming the at least one pore by exposing the at least one of the first substrate, the second substrate, or the interfacial material to chemical processing, as indicated at act **308**. In some examples, forming the at least one pore or recess may involve forming the at least one recess by selectively etching a portion of the interfacial material between the first substrate and the second substrate to recess the interfacial material relative to the first substrate and the second substrate, as indicated at act **310**. In some examples, forming the at least one pore or recess comprises forming the at least one recess by selectively etching regions of oxide material interposed between regions of non-oxide material of at least one of the first substrate or the second substrate to recess each region of the oxide material relative to adjacent regions of the non-oxide material, as indicated at act **312**. In some examples, forming the at least one pore or recess may involve rendering a material of a region of at least one of the first substrate or the second substrate partially defining the cavity porous through chemical treatment or by patterning and selective etching of the substrate, as indicated at act **314**.

(40) In some examples, the method **300** may involve placing the second substrate comprising the region between, and bonding the second substrate to, the first substrate and a third substrate of the body, as indicated at act **316**. In some examples, the region may be placed proximate to the interface between the first substrate and the second substrate, as indicated at act **318**. In some examples, forming the cavity may involve rendering a diameter of the cavity proximate to the region less than a diameter of the cavity distal from the region, as indicated at act **320**. In some examples, rendering the material of the region of the at least one of the first substrate or the second substrate partially defining the cavity porous may involve rendering the material of a first region of the first substrate partially defining the cavity porous to form a first mass of the porous material and rendering a material of a second region of the second substrate partially defining the cavity porous to form a second mass of the porous material, as indicated at act **322**. In some examples, the first and the second porous regions may be placed distal from the interface between the first substrate and the second substrate, as indicated at act **324**.

(41) The ordering and arrows of the acts in the flowchart of FIGS. **3A** and **3B** are not to be interpreted to imply that those acts must or should be performed in a specific order. When it is logically possible to do so, the acts in the flowchart of FIGS. **3A** and **3B** may be performed in any order. For example, the cavity may be defined in the body, as stated in act **304**, before the body is provided (i.e., when the cavity has been preformed as part of the body), after the formation of at least one pore or recess, or before or after any of acts **308** through **324**. In addition, the dashed lines indicating acts **308** through **324** are optional in some examples should not be interpreted to mean that any of acts **302**, **304**, or **306**, or the order in which they are presented, is not optional.

(42) FIGS. **4A** and **4B** are schematics of illustrative systems **402** and **416**, respectively, including a vapor cell **400** in accordance with this disclosure, differing in whether microwaves are applied directly to the vapor cell **400**, as in a microwave-optical double-resonance clock or an Mx magnetometer shown in system **402**, or applied as modulation to a laser bias current, as in a clock based on coherent population trapping or a Bell-Bloom type magnetometer shown in system **416**. The systems **402** and **416** may be configured as, for example, atomic clocks, magnetometers, or gyroscopes.

(43) The vapor cell **400** may include an examination region containing vaporized atoms of the subject material, and one or more emitters may be configured to direct electromagnetic radiation of a known type and intensity toward the examination region (e.g., one or more lasers **408**,

microwaves **412**, both lasers **408** and microwaves **412**, without limitation). Such a vapor cell **400** may be maintained at near-vacuum pressure or may include a buffer gas. By way of example only, the buffer gas may include a mixture of N.sub.2 and argon. A detector **414** may include a sensor configured to detect the transmitted radiation and therefore determine one or more properties of the vaporized atoms of the subject material in response to the transmitted radiation. For example, the sensor of the detector **414** may be configured to detect the transition of electrons of the subject material between energy levels, responsive to the energy from a first of the emitters (e.g., from the laser **408**), as measured in variation of signal strengths relative to the spectrum of the radiation, e.g., from the microwave **412**.

(44) One or more signals representative of the properties measured by the detector **414** may be provided as feedback to an oscillator **406**. The oscillator **406** may be used to generate a clock output **404**, which may be used as a clock signal itself or may be used to verify or synchronize another clock signal. In other words, the oscillator **406** may generate a clock output **404** whose frequency is determined by energy level differences in the subject material.

(45) Providing recesses or pores in a body of a vapor cell may induce one or more exposed surfaces of a subject liquid within the vapor cell to exhibit a concave shape. As a nonlimiting example, the size, shape, position, and configuration of the recesses or pores may have capillary-like characteristics, causing any subject material condensed within the recesses or pores to have a negative meniscus. In accordance with the Kelvin equation, the concave shape of the exposed surfaces of the masses of subject material may cause the vapor pressure to be less than the saturation pressure for the subject material above a flat liquid surface. Such control over the vapor pressure may enable devices utilizing the vapor cells, such as, for example, atomic clocks, to operate reliably over a greater range of operating temperatures.

(46) Such a system **402** or **416** may be particularly useful for generating, verifying, or synchronizing clock signals of high accuracy and/or in extreme environmental conditions. Systems **402** and **416** in accordance with this disclosure may find application in the aerospace industry (e.g., to control clock signals in satellites and spacecraft), the automotive industry, the telecommunications and banking industries (e.g., to verify or set clock signals for relevant computing systems), and in standard-setting situations (e.g., to establish timings for relevant standards). By reducing the vapor pressure of the subject material in the vapor cell of the system **402** or **416**, the atomic clock may operate over a larger range of ambient temperatures.

(47) Techniques for forming recesses and/or pores, as disclosed herein, may enable formation of recesses and/or pores having selectable sizes, shapes, volumes, and positions in vapor cells. Such techniques may enable selection and variation in the volume of subject material receivable by the recesses and/or pores, and accompanying flexibility in size of the vapor cell, quantity of subject material in the cavity of the vapor cell, and operating parameters for vapor cells.

(48) While certain illustrative examples have been described in connection with the figures, the scope of this disclosure is not limited to those examples explicitly shown and described in this disclosure. Rather, many additions, deletions, and modifications to the examples described in this disclosure may be made to produce examples within the scope of this disclosure, such as those specifically claimed, including legal equivalents. In addition, features from one disclosed example may be combined with features of another disclosed example while still being within the scope of this disclosure.

Claims

1. A vapor cell, comprising: a body defining a cavity within the body, the body comprising a first substrate bonded to a second substrate at an interface, a first window located on a side of the first substrate opposite the second substrate, and a second window located on a side of the second substrate opposite the first substrate; the first substrate comprising a first porous volume extending

around a circumference of the cavity and located proximate to the first window; and the second substrate comprising a second porous volume extending around the circumference of the cavity and located proximate to the second window.

2. The vapor cell of claim 1, wherein the porous volume defines at least one recess or pore, a smallest dimension of the at least one recess or pore being about 500 microns or less, as measured in a direction parallel to at least one surface of the first substrate partially defining the cavity.

3. The vapor cell of claim 1, comprising an interfacial material interposed between the first substrate and the second substrate.

4. The vapor cell of claim 3, wherein the interfacial material comprises an oxide material.

5. The vapor cell of claim 3, wherein the interfacial material is nonporous.

6. The vapor cell of claim 1, wherein: the first porous volume occupies a first portion of a first surface of the first substrate exposed to the cavity; the second porous volume occupies a second portion of a second surface of the second substrate exposed to the cavity; and remainders of the first surface of the first substrate and of the second surface of the second substrate are nonporous.

7. The vapor cell of claim 1, wherein a first depth of the first porous volume is non-constant and a second depth of the second porous volume is non-constant.

8. The vapor cell of claim 7, wherein the first depth and the second depth are greatest proximate to the cavity.

9. The vapor cell of claim 1, wherein at least a portion of a boundary between the first porous volume and a remainder of the first substrate is arcuate.

10. The vapor cell of claim 9, wherein a first cross-sectional shape of the first porous volume and a second cross-sectional shape of the second porous volume is at least substantially quarter-circular.

11. The vapor cell of claim 1, wherein a height of the body is between about 1,000 μm and about 2,000 μm .

12. A method of making a vapor cell, comprising: rendering a first portion of a first substrate porous; rendering a second portion of a second substrate porous; removing material of the first substrate at a dimension smaller than the first portion to define a first portion of a cavity and to leave a first porous volume extending around a circumference of the first portion of the cavity; removing material of the second substrate at the dimension to define a second portion of the cavity and to leave a second porous volume extending around a circumference of the second portion of the cavity; bonding the first substrate to the second substrate to form a body defining the cavity within the body; bonding a first window to the first substrate on a side of the first substrate opposite the second substrate, with the first porous volume proximate to the first window; and bonding a second window to the second substrate on a side of the second substrate opposite the first substrate, with the second porous volume proximate to the second window.

13. The method of claim 12, wherein: rendering the first portion of the first substrate porous comprises forming in the first substrate at least one pore or recess having a smallest dimension of about 500 microns or less; and rendering the second portion of the second substrate porous comprises forming in the second substrate at least another pore or recess having a smallest dimension of about 500 microns or less.

14. The method of claim 13, wherein forming the at least one pore or recess and forming the at least another pore or recess comprises subjecting portions of the first substrate and the second substrate to chemical processing.

15. The method of claim 13, wherein forming the at least one pore or recess and forming the at least another pore or recess comprises anodizing portions of the first substrate and the second substrate or stain etching the portions of the first substrate and the second substrate.

16. The method of claim 12, wherein removing the material of the first substrate comprises drilling the first substrate and wherein removing the material of the second substrate comprises drilling the second substrate.

17. The method of claim 12, wherein bonding the first substrate to the second substrate comprises

performing a contact and anneal process on the first substrate and the second substrate.

18. The method of claim 12, wherein bonding the first window to the first substrate comprises anodic bonding the first window to the first substrate and wherein bonding the second window to the second substrate comprises anodic bonding the second window to the second substrate.

19. A system, comprising: an emitter positioned and oriented to direct radiation through windows of a vapor cell; and a detector positioned and oriented to detect the radiation; wherein the vapor cell comprises a body defining a cavity within the body, the body comprising: a first substrate bonded to a second substrate at an interface; a first window located on a side of the first substrate opposite the second substrate; and a second window located on a side of the second substrate opposite the first substrate; the first substrate comprising a first porous volume extending around a circumference of the cavity and located proximate to the first window; and the second substrate comprising a second porous volume extending around the circumference of the cavity and located proximate to the second window.

20. The system of claim 19, comprising an oscillator positioned and configured to receive one or more signals representative of properties measured by the detector.
