

TERAHERTZ IMAGER AND METHOD OF FORMING THE SAME**CROSS-REFERENCE TO RELATED APPLICATION**

[0001] This application claims the benefit of priority of Singapore application No. 10202400139W filed January 17, 2024, the contents of it being hereby incorporated by reference in its entirety for all purposes.

TECHNICAL FIELD

[0002] Various embodiments of this disclosure may relate to a terahertz imager. Various embodiments of this disclosure may relate to a method of forming a terahertz imager.

BACKGROUND

[0003] Multispectral terahertz (THz) imagers are vital for water and chemical sensing in space, agricultural and pharmaceutical applications. Multispectral terahertz imagers include three parts – (i) an absorber, (ii) a sensing element and (iii) a tunable element. The functionality of the absorber is to absorb the incident THz wave and convert the THz wave into heat. To achieve high absorption, Absorption (A) = 1 – Transmission (T) – Reflection (R), the transmission (T) and reflection (R) should ideally be 0.

[0004] Hence, the absorber includes three layers – (a) reflector layer – to prevent any transmission (i.e., $T = 0$), (b) spacer layer – dielectric layer to absorb the THz wave and (c) metasurface layer – to reduce the surface reflection through impedance matching to free space (i.e., $R = 0$). Hence, a good absorber will absorb all the energy at the designed frequency and convert it into heat. Then, the sensing element is used to measure this temperature change as a change in electrical parameter, for e.g., resistance change in bolometer or current pulse in pyroelectric sensors. The tunable element is used to tune the frequency of THz wave that will be absorbed.

SUMMARY

[0005] Various embodiments may relate to a terahertz (THz) imager. The terahertz imager may include a reflector layer. The terahertz imager may also include an absorber on the reflector layer. The absorber may be or may include a dielectric spacer. The terahertz imager

may further include a microelectromechanical system (MEMS)-based metasurface on or over the absorber. The terahertz imager may additionally include a sensing layer.

[0006] Various embodiments may relate to a method of forming a terahertz (THz) imager. The method may include forming a reflector layer. The method may also include forming an absorber on the reflector layer, the absorber comprising a dielectric spacer. The method may further include forming a microelectromechanical system (MEMS)-based metasurface over the absorber. The method may additionally include forming a sensing layer.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] In the drawings, like reference characters generally refer to the same parts throughout the different views. The drawings are not necessarily drawn to scale, emphasis instead generally being placed upon illustrating the principles of various embodiments. In the following description, various embodiments of the invention are described with reference to the following drawings.

FIG. 1 shows a schematic of a terahertz (THz) imager according to various embodiments.

FIG. 2 shows a general illustration of a method of forming a terahertz (THz) imager according to various embodiments.

FIG. 3A shows a schematic of a cross-sectional side view of a terahertz imager according to various embodiments.

FIG. 3B shows a schematic of a top view of the terahertz imager shown in FIG. 3A according to various embodiments.

FIG. 4A shows a schematic illustrating the wafer bonding and grinding approach according to various embodiments.

FIG. 4B shows (left) a plot of simulated absorptivity as a function of frequency (in terahertz or THz) illustrating the absorptivity of different thicknesses of silicon (Si) spacers according to various embodiments, and (right) a plot of peak absorptivity as a function of silicon spacer thickness (in micrometers or μm) illustrating the suitable thickness of the silicon (Si) spacer to be used in the terahertz imager according to various embodiments.

FIG. 4C shows (a) a scanning acoustic microscopy (C-SAM) image of a bonded and grinded silicon (Si) wafer with only two minor chip-offs at top and bottom of the wafer according to various embodiments; (b) the optical microscopy image of the top chip-off of the bonded and

grinded wafer according to various embodiments; (c) the optical microscopy image of the bottom chip-off of the bonded and grinded wafer according to various embodiments; and (d) a table illustrating thicknesses of the silicon (Si) wafer achieved according to various embodiments during two test runs.

FIG. 4D is a schematic comparing a terahertz imager including the microelectromechanical system (MEMS)-based metasurface according to various embodiments and a conventional imager.

FIG. 5 shows (above) a plot of absorption (in percent or %) as a function of frequency (in terahertz or THz); and (below) a table showing various experimental parameters for an imager having a metasurface with circular/closed ring resonators (CRR) according to various embodiments.

FIG. 6A shows a schematic of a metasurface with a cantilever resonator according to various embodiments.

FIG. 6B shows a plot of frequency (in terahertz or THz)/ peak absorption as a function of cantilever length (in micrometers or μm) illustrating the simulation (Sim) results for various cantilever lengths according to various embodiments.

FIG. 6C shows a plot of absorption (in percent or %) as a function of frequency (in terahertz or THz) illustrating the experimental results for devices with various cantilever lengths according to various embodiments.

FIG. 7A shows a plot of absorption as a function of frequency (in terahertz or THz) illustrating the peak absorption frequencies at different bend angles according to various embodiments.

FIG. 7B shows a plot of frequency (in terahertz or THz)/ absorption as a function of bend angle (in degrees or $^{\circ}$) illustrating the spectral tunability of an imager with a microelectromechanical system (MEMS)-based metasurface according to various embodiments, with the inset showing a cantilever resonator of the MEMS-based metasurface according to various embodiments at a specific bend angle.

FIG. 8A shows a plot of reflection amplitude as a function of frequency (in terahertz or THz) illustrating the spectral tunability of a device with a silicon (Si) spacer according to various embodiments.

FIG. 8B shows a plot of reflection amplitude as a function of frequency (in terahertz or THz) illustrating the spectral tunability of a device with a silica (SiO_2) spacer according to various embodiments.

FIG. 9A shows a cross-sectional schematic of an absorber device according to various embodiments.

FIG. 9B shows (left) a top view of the metasurface of the absorber device shown in FIG. 9A according to various embodiments; and (right) a top view of a unit cell of the metasurface according to various embodiments.

FIG. 9C shows a table illustrating the thicknesses and materials of the various layers of the absorber device shown in FIG. 9A according to various embodiments.

FIG. 10A shows a cross-sectional schematic of an absorber device according to various embodiments.

FIG. 10B shows (left) a top view of the metasurface 1006 of the absorber device shown in FIG. 10A according to various embodiments; and (right) a top view of a unit cell of the metasurface 1006 according to various embodiments.

FIG. 10C shows a table illustrating the thicknesses and materials of the various layers of the absorber device shown in FIG. 10A according to various embodiments.

FIG. 11 shows a cross-sectional schematic of a terahertz imager according to various embodiments.

FIG. 12 shows a cross-sectional schematic of a terahertz imager according to various embodiments.

FIG. 13 shows a table illustrating the thicknesses and materials of the various layers of the structures shown in FIGS. 11 - 12 according to various embodiments.

FIG. 14 shows a cross-sectional schematic of a multi-spectral terahertz imager according to various embodiments.

FIG. 15 shows a cross-sectional schematic of a multi-spectral terahertz imager according to various embodiments.

FIG. 16 shows a table illustrating the thicknesses and materials of the various layers/features of the structures shown in FIGS. 14 - 15 according to various embodiments.

FIG. 17 shows a cross-sectional schematic of a multi-spectral terahertz imager according to various embodiments.

FIG. 18 shows a cross-sectional schematic of a multi-spectral terahertz imager according to various embodiments.

FIG. 19 shows a cross-sectional schematic of a multi-spectral terahertz imager according to various embodiments.

DESCRIPTION

[0008] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized, and structural, logical, and electrical changes may be made without departing from the scope of the invention. The various embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

[0009] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0010] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements.

[0011] In the context of various embodiments, the term “about” or “approximately” as applied to a numeric value encompasses the exact value and a reasonable variance, e.g., within 10% of the specified value.

[0012] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0013] By “comprising” it is meant including, but not limited to, whatever follows the word “comprising”. Thus, use of the term “comprising” indicates that the listed elements are required or mandatory, but that other elements are optional and may or may not be present.

[0014] By “consisting of” it is meant including, and limited to, whatever follows the phrase “consisting of”. Thus, the phrase “consisting of” indicates that the listed elements are required or mandatory, and that no other elements may be present.

[0015] Embodiments described in the context of one of the imagers are analogously valid for the other imagers. Similarly, embodiments described in the context of a method are analogously valid for an imager, and vice versa.

[0016] FIG. 1 shows a schematic of a terahertz (THz) imager according to various embodiments. The terahertz imager may include a reflector layer 102. The terahertz imager may also include an absorber 104 in contact with the reflector layer 102. The absorber 104 may be or may include a dielectric spacer. The terahertz imager may further include a microelectromechanical system (MEMS)-based metasurface 106 on or over the absorber 104. The terahertz imager may additionally include a sensing layer 108.

[0017] In other words, the terahertz imager may include absorber 104 with a reflector layer 102 in contact with the absorber 104. The terahertz imager may also include a microelectromechanical system (MEMS)-based metasurface 106 such that the absorber 104 is between the reflector layer 102 and the microelectromechanical system (MEMS)-based metasurface 106. The terahertz imager may additionally include a sensing layer 108.

[0018] For avoidance of doubt, FIG. 1 seeks to illustrate certain features of a terahertz imager according to various embodiments, and is not intended to limit, for instance, the dimensions, shape, size, or orientation. For example, the reflector layer 102, the absorber 104, the metasurface 106 and the sensing layer 108 may be of any suitable thicknesses. Also, while FIG. 1 shows the sensing layer 108 on the absorber 104, the sensing layer 108 may alternatively be at any other suitable position.

[0019] The absorber 104 may be configured to generate heat in response to terahertz waves incident onto the absorber 104. The sensing layer 108 may be configured to detect a temperature change due to the heat generated by the absorber 104. The reflector layer 102 may be configured to reduce a transmission of the terahertz waves from the terahertz imager. The MEMS-based metasurface 106 may be configured to be movable (in response to application of an external voltage or current), and may act as a tunable element or filter for filtering the wavelength or range of wavelengths of the terahertz waves passing through to be absorbed by the absorber 104. The terahertz imager may be a multispectral terahertz (THz) imager.

[0020] The dielectric spacer may include any suitable material. In various embodiments, the dielectric spacer may include high resistivity (HR) silicon (i.e., silicon greater than 1 k Ω cm). The HR silicon may be undoped silicon (Si) or may be lightly doped silicon, e.g. less than 10¹⁴ cm⁻³. In various embodiments, the dielectric layer may include a layer of HR silicon and a layer of more heavily doped silicon (e.g., more than 10¹⁴ cm⁻³) in contact with the layer of HR silicon. This may ensure ease of actuation of MEMS devices of the MEMS-based metasurface and at the same time minimize or reduce the impact on the electromagnetic

performance of the absorber 104. The dielectric spacer may have a refractive index of at least 1, e.g., at least 3. Various embodiments may include a single dielectric spacer of HR silicon for improving the tunable range of the imager. In various other embodiments, the dielectric spacer may include silica, silicon nitride, or polyimide.

[0021] The dielectric spacer may have a sub-wavelength thickness. In other words, a thickness of the dielectric spacer may be less than a wavelength of the terahertz waves.

[0022] In various embodiments, various sub-wavelength thicknesses of HR silicon as the dielectric spacer may provide for absorption of THz waves across a broad spectral region.

[0023] One of the major challenges of achieving a high-performance multispectral THz imager is the need for optimized thickness of the dielectric spacer of the absorber 104. For the frequency of 0.3 THz (wavelength, $\lambda = 1000 \mu\text{m}$), the thickness of the dielectric spacer formed with a material with refractive index of n may need to be $60/n$. Hence, a layer of silica SiO_2 ($n = 2.1$) may require a thickness of $28.5 \mu\text{m}$, a layer of silicon nitride SiN ($n = 2.5$) may require a thickness of $24 \mu\text{m}$, a layer of polyimide ($n = 1.7$) may require a thickness of $35 \mu\text{m}$, and a layer of high resistivity silicon Si ($n = 3.4$) may require a thickness of $17 \mu\text{m}$. These thicknesses of dielectric materials may be difficult to achieve using conventional thin film deposition processes. Hence, earlier reported work with unoptimized thickness has shown poor absorption. Alternatively, entire substrates are used as a spacer. However, using the entire substrate may lead to poor absorption, and a higher thermal mass may cause slow device response.

[0024] Various embodiments may have a dielectric spacer with optimized thickness. For instance, the thickness of the dielectric spacer may be less than or equal to $50 \mu\text{m}$, e.g., less than or equal to $35 \mu\text{m}$, less than or equal to $28.5 \mu\text{m}$, less than or equal to $17 \mu\text{m}$.

[0025] In various embodiments, the terahertz imager may include a handle substrate. The handle substrate may be used to provide mechanical support for the dielectric spacer during processing. In various embodiments, the handle substrate may be present in the final device, while in various other embodiments, the handle substrate may be removed from the final device.

[0026] The handle substrate may include any suitable material. The handle substrate may be or may include any semiconductor, polymer and/or plastic. For instance, the handle substrate may include silicon (Si), germanium (Ge), glass, silica (SiO_2) and/or gallium arsenide (GaAs).

[0027] In various embodiments, the terahertz imager may include a bonding stack between the absorber and the handle substrate. The bonding stack may include a bonding interface layer (formed during the bonding process) and/or a bonding material layer (including any suitable bonding material). The bonding material layer may include a suitable material such as titanium, tungsten, platinum, nickel, palladium, aluminum, cobalt or molybdenum, while the bonding interface layer may include a suitable material, such as a respective silicide of the suitable material of the bonding material layer (formed by reaction between silicon and the suitable material), e.g., titanium silicide, tungsten silicide, platinum silicide, nickel silicide, aluminum silicide, cobalt silicide or molybdenum silicide. In various embodiments, the bonding material layer may include a diffusion barrier layer for preventing or reducing diffusion of bonding material into the top stack, e.g., the absorber 104. The diffusion barrier layer may include a suitable material such as titanium nitride or tantalum nitride.

[0028] In various embodiments, the reflector layer 102 may be a standalone layer, for instance, in the bonding stack, while in various other embodiments, the reflector layer 102 may be one of two electrode layers adjoining the sensing layer 108. The reflector layer 102 may include any suitable material, e.g., aluminum (Al), molybdenum (Mo), titanium (Ti) or copper (Cu). Generally speaking, metals may be used for bonding and as a reflector layer.

[0029] In various embodiments, the sensing layer 108 may be configured for bolometric sensing or for pyroelectric thermal sensing. When the sensing layer 108 is configured for bolometric sensing, the sensing layer 108 may include a material with a high temperature coefficient of resistance (TCR), such as amorphous silicon (a-Si) or vanadium oxide (VO_x). When the sensing layer 108 is configured for pyroelectric thermal sensing, the imager may also include two electrode layers adjoining the sensing layer 108, and the sensing layer 108 may include a suitable pyroelectric material such as aluminum nitride (AlN) or scandium aluminum nitride (ScAlN).

[0030] In various embodiments, microelectromechanical system (MEMS)-based metasurface 106 may include a plurality of elements or structures. The plurality of elements or structures may be arranged in an array. A pitch between neighboring elements or structures of the plurality of elements or structures may be sub-wavelength, i.e., less than a wavelength of the terahertz waves. The elements or structures may include any suitable material, e.g., aluminum (Al), molybdenum (Mo), titanium (Ti) or copper (Cu). The microelectromechanical system (MEMS)-based metasurface 106 may allow for multi-spectral imaging.

[0031] FIG. 2 shows a general illustration of a method of forming a terahertz (THz) imager according to various embodiments. The method may include, in 202, forming a reflector layer. The method may also include, in 204, forming an absorber in contact with the reflector layer, the absorber including a dielectric spacer. The method may further include, in 206, forming a microelectromechanical system (MEMS)-based metasurface over the absorber. The method may additionally include, in 208, forming a sensing layer.

[0032] In other words, various embodiments of forming a terahertz (THz) imager may include forming a reflector layer, an absorber with a dielectric spacer, a MEMS-based metasurface and a sensing layer.

[0033] For avoidance of doubt, FIG. 2 is not intended to limit the sequence of the various steps. For instance, if the sensing layer is between the absorber layer and the MEMS-based metasurface, the absorber layer may be formed first (e.g., by grinding, step 204), followed by forming of the sensing layer (step 208) and forming of the MEMS-based metasurface (step 206). On the other hand, if the reflector layer is between the absorber and the sensing layer, the reflector layer may be formed first (step 202), followed by forming of the sensing layer (step 208) and grinding to form the absorber (step 204).

[0034] In various embodiments, the method may include forming the reflector layer, the absorber, the microelectromechanical system (MEMS)-based metasurface and the sensing layer over a handle substrate. The handle substrate may include any suitable material, e.g., silicon, germanium, glass, silica and/or gallium arsenide.

[0035] In various embodiments, the method may include forming a bonding stack on the handle substrate such that the bonding layer is between the absorber and the handle substrate.

[0036] In various embodiments, the absorber may be configured to generate heat in response to terahertz waves incident onto the absorber. The sensing layer may be configured to detect a temperature change due to the heat generated by the absorber. The reflector layer may be configured to reduce a transmission of the terahertz waves from the terahertz imager.

[0037] The dielectric spacer may include any suitable material. In various embodiments, the dielectric spacer may include high resistivity (HR) silicon. The dielectric spacer may have a refractive index of at least 1, e.g., at least 3.

[0038] In various embodiments, a thickness of the dielectric spacer may be less than a wavelength of the terahertz waves. Various embodiments may have a dielectric spacer with optimized thickness. For instance, the thickness of the dielectric spacer may be less than or

equal to 50 μm , e.g., less than or equal to 35 μm , less than or equal to 28.5 μm , less than or equal to 17 μm .

[0039] Various embodiments may include a terahertz imager including an absorber stack (including an absorber, and a MEMS-based metasurface), a sensing stack or a sensing layer, a bonding stack and a handle substrate. The terahertz imager may include a reflector layer, which may be part of the absorber stack, the bonding stack or the sensing stack.

[0040] FIG. 3A shows a schematic of a cross-sectional side view of a terahertz imager according to various embodiments. FIG. 3B shows a schematic of a top view of the terahertz imager shown in FIG. 3A according to various embodiments. The terahertz imager may include a reflector layer 302, an absorber/dielectric spacer 304 on the reflector layer 302, and a MEMS-based metasurface 306 over the absorber 304. The terahertz imager may include a sensing layer 308. The reflector layer 302 may be one of two electrodes included in the terahertz imager and may be in contact with the sensing layer 308. The reflector layer 302 may be on the sensing layer 308. The sensing layer 308 may be on a remaining electrode 310 of the two electrodes. The terahertz imager may also include a handle substrate 312, and a bonding stack 314 on the handle substrate 312. The remaining electrode 310 may be on the bonding stack 314. The bonding stack 314 may include a bonding interface layer 314a on the handle substrate 312, a bonding material layer 314b on the bonding interface layer 314a, and a diffusion barrier layer 314c on the bonding material layer 314b.

[0041] The reflector layer 302 may prevent any transmission of THz waves through the reflector layer 302. Hence, the reflector layer 302 may be an electrically conductivity layer with a thickness greater than skin depth. For experiments described herein, a 200 nm thick aluminum layer may be used as a reflector layer for terahertz waves of 0.3 THz ($\lambda = 1000 \mu\text{m}$).

[0042] The dielectric spacer 304 may be configured to absorb the incident THz wave and provide destructive interference of the incident wave and the reflected wave. Hence, an optimized thickness of the dielectric spacer 304 may be required. From simulation, a 17 μm thickness of high-resistivity (HR) Si may provide the best absorption, and a 10% reduction in absorption may be observed for thickness variation of $\pm 1 \mu\text{m}$. Such thicknesses of silicon or any other material maybe quite difficult to be achieved by conventional thin film deposition. Hence, a wafer bonding and grinding approach may be used.

[0043] FIG. 4A shows a schematic illustrating the wafer bonding and grinding approach according to various embodiments. Two silicon (Si) wafers may be bonded, with an Al layer

(which acts as the bottom reflector) on one of the wafers. The top Si wafer may be grinded to the desired thickness t_{Si} , i.e., around 17 μm , to form the dielectric spacer. FIG. 4B shows (left) a plot of simulated absorptivity as a function of frequency (in terahertz or THz) illustrating the absorptivity of different thicknesses of silicon (Si) spacers according to various embodiments, and (right) a plot of peak absorptivity as a function of silicon spacer thickness (in micrometers or μm) illustrating the suitable thickness of the silicon (Si) spacer to be used in the terahertz imager according to various embodiments. FIG. 4B shows that a 17 μm thick Si spacer may achieve peak simulated absorptivity at 0.3 THz. A variance of $\pm 1 \mu\text{m}$ may still allow absorption of over 90%, while a variance of $\pm 3 \mu\text{m}$ may still allow absorption of over 80%. The acceptable thicknesses for the Si spacer may be of a value in the range from about 14 μm to about 21 μm . FIG. 4C shows (a) a scanning acoustic microscopy (C-SAM) image of a bonded and grinded silicon (Si) wafer with only two minor chip-offs at top and bottom of the wafer according to various embodiments; (b) the optical microscopy image of the top chip-off of the bonded and grinded wafer according to various embodiments; (c) the optical microscopy image of the bottom chip-off of the bonded and grinded wafer according to various embodiments; and (d) a table illustrating thicknesses of the silicon (Si) wafer achieved according to various embodiments during two test runs. The tolerance of the wafer bonding and grinding approach may be measured to be $\pm 1 \mu\text{m}$ across the entire 300 mm wafer. FIG. 4C(b) and (c) illustrate high quality bonding of the wafer and no presence of unacceptable defects in the wafer.

[0044] For the structure shown in FIG. 3A, the sensing stack (including the sensing layer 308 as well as the two electrodes 302, 310) may be formed on a first silicon wafer. A second silicon wafer may also be selected to be the handle substrate 312. The diffusion barrier layer 314c may be formed in contact with the sensing stack and the bonding material layer 314b may be formed in contact with the diffusion barrier layer 314c. The layer 314c may act as a diffusion barrier between the bonding material layer 314b and the electrode 310 of the sensing stack. The first silicon wafer may be bonded to a second silicon wafer such that the bonding stack 314 is between the first silicon wafer and the second silicon wafer. The bonding may be carried out under room temperature and atmospheric pressure after nitrogen, oxygen or argon plasma treatment. The bonding interface layer 314a may be formed by reaction between the second silicon wafer and the bonding material layer 314b, e.g., via silicidation. The bonded structure may be annealed at a temperature selected from a range from 150 °C to 400 °C and in nitrogen

(N₂) or vacuum (1E-3 mbar) for enhancing the bonding interface layer 314a. The first silicon wafer may be grinded from the backside to the desired thickness using backgrinding or a dry etch process to form the absorber 304. The first silicon wafer may be grinded from e.g., a thickness of 775 μm to a thickness selected from a range from 5 μm to 100 μm . A MEMS-based metasurface 306 may be formed on or over the absorber 304. The MEMS-based metasurface 306 may be formed on or over the absorber layer 304 by forming a metal layer patterned on the absorber 304, followed by forming a sacrificial oxide layer on the metal layer, followed by formation of the metasurface structures consisting of metal layers only or combination of metal and dielectric layers. Afterwards, the sacrificial oxide layer may be removed to release the metasurface structures.

[0045] The MEMS-based metasurface 306 may be a two-dimensional (2D) array of sub-wavelength elements or structures. The array may have a first periodicity P_x along the x-axis and a second periodicity P_y along the y-axis. In various embodiments, P_x and P_y may be equal, while in various other embodiments, P_x and P_y may be different.

[0046] For the cross-resonator in FIG. 4A, the pitch is 120 μm ($\sim \lambda/8$) and is made by patterning 1 μm thick Al. The shape and geometry of the metasurface may be arbitrary designed, but the size/dimension of each element or structure may be in sub-wavelength. FIG. 4D is a schematic comparing a terahertz imager including the microelectromechanical system (MEMS)-based metasurface according to various embodiments and a conventional imager.

[0047] A MEMS-metasurface with circular ring resonators may also be designed. FIG. 5 shows (above) a plot of absorption (in percent or %) as a function of frequency (in terahertz or THz); and (below) a table showing various experimental parameters for an imager having a metasurface with circular/closed ring resonators (CRR) according to various embodiments. The absorption is measured to be $\sim 100\%$ at 0.51 THz.

[0048] Further, a MEMS-metasurface with unreleased cantilever resonator may be designed. FIG. 6A shows a schematic of a metasurface with a cantilever resonator according to various embodiments. FIG. 6B shows a plot of frequency (in terahertz or THz)/ peak absorption as a function of cantilever length (in micrometers or μm) illustrating the simulation (Sim) results for various cantilever lengths according to various embodiments. FIG. 6C shows a plot of absorption (in percent or %) as a function of frequency (in terahertz or THz) illustrating the experimental results for devices with various cantilever lengths according to various embodiments. L40 denotes a cantilever length of 40 μm , L60 denotes a cantilever

length of 60 μm , L80 denotes a cantilever length of 80 μm , and L100 denotes a cantilever length of 100 μm .

[0049] With increasing cantilever lengths, the peak absorption frequency should decrease as observed from the simulation results shown in FIG. 6B and experimentally confirmed with results shown in FIG. 6C. A high absorption of over 70% may be observed for devices with various cantilever lengths of 40 μm , 60 μm , 80 μm and 100 μm .

[0050] The metasurface layer can be integrated with MEMS technology to achieve spectral tunability as confirmed from the simulation results shown in FIGS. 7A - B. FIG. 7A shows a plot of absorption as a function of frequency (in terahertz or THz) illustrating the peak absorption frequencies at different bend angles according to various embodiments. FIG. 7B shows a plot of frequency (in terahertz or THz)/ absorption as a function of bend angle (in degrees or $^\circ$) illustrating the spectral tunability of an imager with a microelectromechanical system (MEMS)-based metasurface according to various embodiments, with the inset showing a cantilever resonator of the MEMS-based metasurface according to various embodiments at a specific bend angle. An absorption value of 1 in the plots of FIGS. 7A - 7B indicates perfect absorption.

[0051] With decreasing release angles of the cantilevers, the peak absorption frequency can be tuned. In other words, by controlling the angle of curvature of the cantilevers, the absorption may be tuned across a wide range of THz frequencies. The peak absorption may remain over 80% across the tunable range. The height of the cantilevers can be controlled using electrostatic or piezoelectric actuation schemes. Various embodiments may include a controller in electrical connection with the plurality of elements/structures of the MEMS-based metasurface to control a movement of the plurality of elements/structures, or a parameter (e.g., height of the elements/structures or gap between the elements/structures and the absorber/sensing layer). Interestingly, using silicon (Si) in the spacer may have an added advantage of increasing the tunable range (e.g., ~ 2 times) due to the higher refractive index (3.4), compared to other reported dielectric layers such as SiN (2.5), SiO₂ (2.1) or polyimide (1.7).

[0052] FIG. 8A shows a plot of reflection amplitude as a function of frequency (in terahertz or THz) illustrating the spectral tunability of a device with a silicon (Si) spacer according to various embodiments. FIG. 8B shows a plot of reflection amplitude as a function of frequency (in terahertz or THz) illustrating the spectral tunability of a device with a silica (SiO₂) spacer according to various embodiments. The simulation results in FIGS. 8A-B show that the tunable

range with a Si spacer is 50% of central frequency (f_c), while the tunable range with a SiO₂ spacer is only 28% of f_c . Hence, the use of HR Si may not only allow for close to perfect absorption but may also provide enhanced spectral tunability.

[0053] The sensing layer or stack may be or may include a resistive element for bolometric sensing or pyroelectric thermal sensing. For bolometric sensing, a high temperature coefficient of resistance (TCR) material, such as amorphous silicon (a-Si) or vanadium oxide (VO_x) may be included in the sensing layer. The readout current may be sent across the sensing element to indicate the resistance change due to the change in temperature of the sensing element, corresponding to the temperature change of the absorber due to the power of absorbed THz. For pyroelectric thermal sensing, the sensing stack may include three layers, i.e. electrode layer – sensing layer – electrode layer, as shown in FIG. 3A. The electrodes 302, 310 may be used to read the transient current due to the change in temperature of the pyroelectric material in the sensing layer 308, corresponding to the temperature change of the absorber 304. The sensing layer may include any suitable pyroelectric material such as aluminum nitride (AlN) or scandium aluminum nitride (ScAlN).

[0054] As highlighted above, the top electrode 302 may also act as the reflector layer. The inclusion of HR Si in the dielectric spacer 304 may allow of higher thermal conductivity and with optimized thickness, a lower thermal mass, thereby enabling faster device response.

[0055] As mentioned above, the bonding step may be needed to achieve the optimized thickness (in the range of 10s of micrometers). In various embodiments, metal-based fusion bonding, followed by silicidation may be used. One of the HR Si wafers may be coated with 20 nm titanium nitride TiN (diffusion barrier layer 314c) and 300 nm of titanium Ti (bonding material layer 314b). This Si wafer may be bonded with another normal Si wafer at room temperature and/or annealed at 350 °C for 2 hours. Silicidation may occur to form the bonding interface layer 314a. The low temperature may be important to maintain the integrity of Al reflector layer 302. The fusion bonding may also provide enough bonding strength to sustain the next wafer thinning process to 10 μm using wafer backgrinding step. The diffusion barrier layer 314c may be used to prevent the Ti from going into Al layers 302, 310 and the dielectric spacer 304, as it may adversely affect the absorption of terahertz waves.

[0056] The handle substrate 312 may provide mechanical stability to the thinned dielectric spacer 304 after grinding for further processing. The handle substrate can be any suitable material, and may be formed from any suitable wafer.

[0057] FIG. 9A shows a cross-sectional schematic of an absorber device according to various embodiments. FIG. 9B shows (left) a top view of the metasurface 906 of the absorber device shown in FIG. 9A according to various embodiments; and (right) a top view of a unit cell of the metasurface 906 according to various embodiments. FIG. 9C shows a table illustrating the thicknesses and materials of the various layers of the absorber device shown in FIG. 9A according to various embodiments. The absorber device may include a reflector layer 902, a dielectric spacer 904, a metasurface 906, a handle substrate 912, a bonding interface layer 914a, a bonding material layer 914b and a diffusion barrier layer 914c.

[0058] FIG. 10A shows a cross-sectional schematic of an absorber device according to various embodiments. FIG. 10B shows (left) a top view of the metasurface 1006 of the absorber device shown in FIG. 10A according to various embodiments; and (right) a top view of a unit cell of the metasurface 1006 according to various embodiments. FIG. 10C shows a table illustrating the thicknesses and materials of the various layers of the absorber device shown in FIG. 10A according to various embodiments. The absorber device may include a dielectric spacer 1004, a metasurface 1006, a handle substrate 1012, a bonding stack 1014 which may act as a reflector layer 1002 or may include a reflector layer 1002.

[0059] FIG. 11 shows a cross-sectional schematic of a terahertz imager according to various embodiments. The imager may include a reflector layer 1102, a dielectric spacer 1104 on the reflector layer 1102, a sensing layer 1108 on the dielectric spacer 1104, a metasurface 1106 on the sensing layer 1108, a handle substrate 1112, a bonding interface layer 1114a on the handle substrate 1112, a bonding material layer 1114b on the bonding interface layer 1114 and a diffusion barrier layer 1114c on the bonding material layer 1114b. The dielectric spacer 1104 may be on the diffusion barrier layer 1114c. In contrast to FIG. 3A, the sensing layer 1108 may not have adjoining electrode layers above or below the sensing layer 1108. Instead, the sensing layer 1108 may be on the dielectric spacer 1104, while the metasurface 1106 may be on the sensing layer 1108.

[0060] For the structure shown in FIG. 11, a bonding stack 1114 including a reflector layer 1102, a diffusion barrier layer 1114c in contact with the reflector layer 1102 and a bonding material layer 1114b in contact with the diffusion barrier layer 1114c may be formed on a first wafer. The first wafer may be bonded to a second wafer such that the bonding stack 1114 is between the first wafer and the second wafer. The bonding interface layer 1114a may be formed by reaction between the second wafer and the bonding material layer 1114b. The first wafer

may be grinded from the backside to the desired thickness to form the dielectric spacer 1104. The sensing layer 1108 may be formed on the (i.e. backside) of the first wafer. A metasurface 1106 may be formed on the sensing layer 1108. The second wafer may act as the handle substrate 1112.

[0061] FIG. 12 shows a cross-sectional schematic of a terahertz imager according to various embodiments. The imager may include a sensing stack including a sensing layer 1208, a first electrode layer 1202, and a second electrode layer 1210 which also acts as a reflector layer. The sensing layer 1208 may be on the first electrode layer 1202, and the second electrode layer 1210 may be on the sensing layer 1208. The imager may also include a dielectric spacer 1204 on the second electrode layer 1210, a metasurface 1206 on the dielectric spacer 1204, a handle substrate 1212, and a bonding stack 1214 including a bonding interface layer 1214a, a bonding material layer 1214b and a diffusion barrier layer 1214c. The bonding stack 1214 may be on the handle substrate 1212, while the sensing stack may be on the bonding stack.

[0062] For the structure shown in FIG. 12, the sensing stack (including the sensing layer 1208 as well as the two electrodes 1202, 1210) may be formed on a first wafer. A diffusion barrier layer 1214c in contact with the sensing stack (i.e., layer 1202) and a bonding material layer 1214b in contact with the diffusion barrier layer 1214c may also be formed. The first wafer may be bonded to a second wafer such that the bonding stack 1214 is between the first wafer and the second wafer. The bonding interface layer 1214a may be formed by reaction between the second wafer and the bonding material layer 1214b. The first wafer may be grinded from the backside to the desired thickness to form the dielectric spacer 1204. A metasurface 1206 may be formed on the dielectric spacer 1204. The second wafer may act as the handle substrate 1212.

[0063] FIG. 13 shows a table illustrating the thicknesses and materials of the various layers of the structures shown in FIGS. 11 - 12 according to various embodiments.

[0064] FIG. 14 shows a cross-sectional schematic of a multi-spectral terahertz imager according to various embodiments. The imager may include a reflector layer 1402, a dielectric spacer 1404 on the reflector layer 1402, a sensing layer 1408 on the dielectric spacer 1404, a MEMS-based metasurface 1406 over the sensing layer 1408 with a tunable air gap 1416 between the MEMS-based metasurface 1406 and the sensing layer 1408, a handle substrate 1412, a bonding interface layer 1414a on the handle substrate 1412, a bonding material layer

1414b on the bonding interface layer 1414a and a diffusion barrier layer 1414c on the bonding material layer 1414b.

[0065] For the structure shown in FIG. 14, a bonding stack 1414 including a reflector layer 1402, a diffusion barrier layer 1414c in contact with the reflector layer 1402 and a bonding material layer 1414b in contact with the diffusion barrier layer 1414c may be formed on a first wafer. The first wafer may be bonded to a second wafer such that the bonding stack 1414 is between the first wafer and the second wafer. The bonding interface layer 1414a may be formed by reaction between the second wafer and the bonding material layer 1414b. The first wafer may be grinded from the backside to the desired thickness to form the dielectric spacer 1404. The sensing layer 1408 may be formed on the (i.e. backside) of the first wafer. A MEMS-based metasurface 1406 may be formed over the sensing layer 1408. The second wafer may act as the handle substrate 1412.

[0066] FIG. 15 shows a cross-sectional schematic of a multi-spectral terahertz imager according to various embodiments. The imager may include a sensing stack including a sensing layer 1508, a first electrode layer 1502, and a second electrode layer 1510 which also acts as a reflector layer. The sensing layer 1508 may be on the first electrode layer 1502, and the second electrode layer 1510 may be on the sensing layer 1508. The imager may also include a dielectric spacer 1504 on the second electrode layer 1510, a MEMS-based metasurface 1506 over the dielectric spacer 1504 with a tunable air gap 1516 separating the MEMS-based metasurface 1506 and the dielectric spacer 1504, a handle substrate 1512, and a bonding stack 1514 including a bonding interface layer 1514a, a bonding material layer 1514b and a diffusion barrier layer 1514c. The bonding stack 1514 may be on the handle substrate 1512, while the sensing stack may be on the bonding stack.

[0067] For the structure shown in FIG. 15, the sensing stack (including the sensing layer 1508 as well as the two electrodes 1502, 1510) may be formed on a first wafer. A diffusion barrier layer 1514c in contact with the sensing stack (i.e., layer 1502) and a bonding material layer 1514b in contact with the diffusion barrier layer 1514c may also be formed. The first wafer may be bonded to a second wafer such that the bonding stack 1514 is between the first wafer and the second wafer. The bonding interface layer 1514a may be formed by reaction between the second wafer and the bonding material layer 1514b. The first wafer may be grinded from the backside to the desired thickness to form the dielectric spacer 1504. A MEMS-based

metasurface 1506 may be formed over the dielectric spacer 1504. The second wafer may act as the handle substrate 1512.

[0068] FIG. 16 shows a table illustrating the thicknesses and materials of the various layers/features of the structures shown in FIGS. 14 - 15 according to various embodiments.

[0069] FIG. 17 shows a cross-sectional schematic of a multi-spectral terahertz imager according to various embodiments. The imager may include a sensing stack on the handle substrate. The sensing stack may include a first electrode layer 1702, a sensing layer 1708, and a second electrode layer 1710. The second electrode layer 1710 may be on the handle substrate 1712. The sensing layer 1708 may be on the second electrode layer 1710, while the first electrode layer 1702 may be on the sensing layer 1708. The imager may also include a bonding stack 1714 on the sensing stack may also act as a reflector layer. The bonding stack 1714 may include a diffusion barrier layer 1714c on the first electrode layer 1702, a bonding material layer 1714b on the diffusion barrier layer 1714c, and a bonding interface layer 1714a on the bonding material layer 1714b. The imager may also include a dielectric spacer 1704 on the bonding stack 1714, and a MEMS-based metasurface 1706 on the bonding stack 1714.

[0070] For the structure shown in FIG. 17, the bonding material layer 1714b, the diffusion barrier layer 1714c, and the sensing stack (including the sensing layer 1708 as well as the two electrodes 1702, 1710) may be formed on the handle substrate 1712, which may be a wafer. This wafer may be bonded to a further wafer such that the bonding stack 1714 and the sensing stack are between the two wafers. The bonding interface layer 1714a may be formed by reaction between the further wafer and the bonding material layer 1714b. The further wafer may be grinded from the backside to the desired thickness to form the dielectric spacer 1704. A MEMS-based metasurface 1706 may be formed over the dielectric spacer 1704.

[0071] FIG. 18 shows a cross-sectional schematic of a multi-spectral terahertz imager according to various embodiments. The imager may include a handle substrate 1812, a bonding stack 1814 on the handle substrate 1812, a dielectric spacer 1804 on the bonding stack 1814, a sensing layer 1808 on the dielectric spacer 1804, and a MEMS-based metasurface 1806 over the sensing layer 1808. The bonding stack 1814 may include a bonding interface layer 1814a on the handle substrate 1812, a bonding material layer 1814b on the bonding interface layer 1814a, and a diffusion barrier layer 1814c on the bonding material layer 1814b. One and/or all of the layers in the bonding stack 1814 may function as a reflector layer.

[0072] For the structure shown in FIG. 18, a diffusion barrier layer 1814c and a bonding material layer 1814b in contact with the diffusion barrier layer 1814c may be formed on a first wafer. The first wafer may be bonded to a second wafer such that the bonding stack 1814 is between the first wafer and the second wafer. The bonding interface layer 1814a may be formed by reaction between the second wafer and the bonding material layer 1814b. The first wafer may be grinded from the backside to the desired thickness to form the dielectric spacer 1804. The sensing layer 1808 may be formed on the (i.e. backside) of the first wafer. A MEMS-based metasurface 1806 may be formed over the sensing layer 1808. The second wafer may act as the handle substrate 1812.

[0073] FIG. 19 shows a cross-sectional schematic of a multi-spectral terahertz imager according to various embodiments. The imager may include a handle substrate 1912, a bonding stack 1914 on the handle substrate 1912, a dielectric spacer 1904 on the bonding stack 1914, a sensing layer 1908 over the dielectric spacer 1904, and a MEMS-based metasurface 1906 on the sensing layer 1908. The bonding stack 1914 may include a bonding interface layer 1914a on the handle substrate 1912, a bonding material layer 1914b on the bonding interface layer 1914a, and a diffusion barrier layer 1914c on the bonding material layer 1914b. One and/or all of the layers in the bonding stack 1914 may function as a reflector layer.

[0074] For the structure shown in FIG. 19, a diffusion barrier layer 1914c and a bonding material layer 1914b in contact with the diffusion barrier layer 1914c may be formed on a first wafer. The first wafer may be bonded to a second wafer such that the bonding stack 1914 is between the first wafer and the second wafer. The bonding interface layer 1914a may be formed by reaction between the second wafer and the bonding material layer 1914b. The first wafer may be grinded from the backside to the desired thickness to form the dielectric spacer 1904. The sensing layer 1908 may be formed on the (i.e. backside) of the first wafer. A MEMS-based metasurface 1906 may be formed over the sensing layer 1908. The second wafer may act as the handle substrate 1912.

Claims

1. A terahertz imager comprising:
 - a reflector layer;
 - an absorber in contact with the reflector layer, the absorber comprising a dielectric spacer;
 - a microelectromechanical system (MEMS)-based metasurface over the absorber; and
 - a sensing layer.
2. The terahertz imager according to claim 1,
 - wherein the absorber is configured to generate heat in response to terahertz waves incident onto the absorber; and
 - wherein the sensing layer is configured to detect a temperature change due to the heat generated by the absorber.
3. The terahertz imager according to claim 1,
 - wherein the reflector layer is configured to reduce a transmission of the terahertz waves from the terahertz imager.
4. The terahertz imager according to claim 1,
 - wherein the dielectric spacer comprises high resistivity (HR) silicon.
5. The terahertz imager according to claim 1,
 - wherein the dielectric spacer has a refractive index of at least 3.

6. The terahertz imager according to claim 1,
wherein a thickness of the dielectric spacer is less than a wavelength of the terahertz waves.
7. The terahertz imager according to claim 6,
wherein the thickness of the dielectric spacer is less than or equal to 50 μm .
8. The terahertz imager according to claim 1, further comprising:
a handle substrate.
9. The terahertz imager according to claim 8,
wherein the handle substrate comprises silicon, germanium, glass, silica or gallium arsenide.
10. The terahertz imager according to claim 8, further comprising:
a bonding stack between the absorber and the handle substrate.
11. A method of forming a terahertz imager, the method comprising:
forming a reflector layer;
forming an absorber in contact with the reflector layer, the absorber comprising a dielectric spacer;
forming a microelectromechanical system (MEMS)-based metasurface over the absorber; and
forming a sensing layer.
12. The method according to claim 11, further comprising:

forming the reflector layer, the absorber, the microelectromechanical system (MEMS)-based metasurface and the sensing layer over a handle substrate.

13. The method according to claim 12,

wherein the handle substrate comprises silicon, germanium, glass, silica or gallium arsenide.

14. The method according to claim 12, further comprising:

forming a bonding stack on the handle substrate such that the bonding layer is between the absorber and the handle substrate.

15. The method according to claim 11,

wherein the absorber is configured to generate heat in response to terahertz waves incident onto the absorber; and
wherein the sensing layer is configured to detect a temperature change due to the heat generated by the absorber.

16. The method according to claim 11,

wherein the reflector layer is configured to reduce a transmission of the terahertz waves from the terahertz imager.

17. The method according to claim 11,

wherein the dielectric spacer comprises high resistivity (HR) silicon.

18. The method according to claim 11,

wherein the dielectric spacer has a refractive index of at least 3.

19. The method according to claim 11,
wherein a thickness of the dielectric spacer is less than a wavelength of the terahertz waves.
20. The method according to claim 19,
wherein the thickness of the dielectric spacer is less than or equal to 50 μm .