

DETECTOR

Cross-Reference To Related Application

- 5 [0001] This application claims the benefit of priority of Singapore patent application No. 201203271-0, filed 3 May 2012, the content of it being hereby incorporated by reference in its entirety for all purposes.

Technical Field

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- [0002] Various embodiments relate to a detector.

Background

- 15 [0003] Microelectromechanical systems (MEMS) based uncooled far infrared (FIR) sensors (microbolometer) are currently gaining more attention due to their wide application areas, e.g. traffic safety, fire fighting or heat leakage detection in buildings. The most common sensor in this field is represented by the resistive infrared (IR) sensor type, which by physical laws is limited by its $1/f$ (1/frequency) and thermal noise.
- 20 Additionally, this kind of sensor suffers from self heating, which with higher ambient temperature, this becomes more critical. Higher ambient temperature will also cause a significant drop in sensing resistance, since semiconductor materials are used for the sensing layer, such that the sensing resistance becomes smaller than the series system resistance, which makes readout impossible.
- 25 [0004] Film bulk acoustic resonator (FBAR) based IR-sensors have been demonstrated to have a very good NETD (Noise Equivalent Temperature Difference) of <10 mK, but due to their non-compatibility with complementary metal-oxide-semiconductor (CMOS) and their huge structures, it is impossible to mass product this kind of sensors.

Summary

[0005] According to an embodiment, a detector is provided. The detector may include a surface excited acoustic wave (SEAW) resonator including a pair of electrodes and a piezoelectric material, the piezoelectric material being electrically coupled to the pair of electrodes, the SEAW resonator configured to generate a surface excited acoustic wave; and a substrate, wherein the SEAW resonator and the substrate are spaced apart from each other by a gap, and wherein the detector is configured to determine a frequency shift of the surface excited acoustic wave in response to an electromagnetic signal incident on the detector.

Brief Description of the Drawings

[0006] In the drawings, like reference characters generally refer to like parts throughout the different views. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the following description, various embodiments of the invention are described with reference to the following drawings, in which:

[0007] FIG. 1A shows a schematic block diagram of a detector, according to various embodiments.

[0008] FIGS. 1B and 1C respectively show cross-sectional representations of the detector of the embodiment of FIG. 1A, according to various embodiments.

[0009] FIG. 2A shows a schematic perspective view of a detector, according to various embodiments.

[0010] FIG. 2B shows schematic top views of respective electrode configurations for a detector, according to various embodiments.

[0011] FIG. 2C shows a schematic top view of a detector, according to various embodiments.

[0012] FIG. 2D shows a partial 3D perspective view of the simulated vibration mode of a radial surface excited acoustic wave sensor, according to various embodiments.

[0013] FIGS. 3A to 3K show, as cross-sectional views, various processing stages of a method for manufacturing a detector, according to various embodiments.

[0014] FIG. 4 shows a plot of simulation results for the bolometer temperature against the response time, according to various embodiments.

5 [0015] FIG. 5A shows a scanning electron microscopy image of a detector, according to various embodiments.

[0016] FIG. 5B shows a plot of frequency shift against temperature for the detector of the embodiment of FIG. 5A.

10 [0017] FIG. 5C shows a plot of resonance frequency shift for the detector of the embodiment of FIG. 5A for different temperatures.

[0018] FIG. 6A shows a 3D perspective view of a simulated radial surface excited acoustic wave sensor, according to various embodiments.

[0019] FIG. 6B shows a partial cross sectional view of a simulated radial surface excited acoustic wave sensor with a top aluminum layer, according to various embodiments.

15 [0020] FIG. 6C shows a partial cross sectional view of a simulated radial surface excited acoustic wave sensor with no aluminum layer or ring, according to various embodiments.

[0021] FIG. 6D shows a partial cross sectional view of a simulated radial surface excited acoustic wave sensor with a bottom aluminum ring, according to various embodiments.

20 [0022] FIG. 6E shows a plot of simulation results for the temperature coefficient of frequency (TCF) for respective radial surface excited acoustic wave sensors of the embodiments of FIGS. 6B to 6D.

[0023] FIG. 6F shows a plot of the frequency shift for the radial surface excited acoustic wave sensor of the embodiment of FIG. 6D for different temperatures.

25 [0024] FIG. 7A shows a simulated temperature distribution of a detector, according to various embodiments.

[0025] FIG. 7B shows a plot of time dependent thermal behavior of the detector of the embodiment of FIG. 7A.

30 [0026] FIGS. 8A and 8B respectively show a schematic top view of a respective detector having a surface excited acoustic wave (SEAW) resonator with four and six coupling sites, respectively, according to various embodiments.

[0027] FIGS. 8C and 8D respectively show a schematic top view of a respective detector having a surface excited acoustic wave (SEAW) resonator with two coupling sites, according to various embodiments.

5 [0028] FIGS. 8E and 8F respectively show plots of the temperature coefficient of frequency (TCF) for the surface excited acoustic wave sensors of the embodiments of FIGS. 8A to 8D.

[0029] FIG. 8G shows a plot of the resonance frequency shift for the detector of the embodiment of FIG. 8B for different temperatures.

10 [0030] FIG. 9A shows a plot of minimal log magnitude against temperature, according to various embodiments.

[0031] FIG. 9B shows a plot of temperature coefficient of frequency (TCF) against temperature, according to various embodiments.

Detailed Description

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[0032] 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.

20 [0033] Embodiments described in the context of one of the methods or devices are analogously valid for the other method or device. Similarly, embodiments described in the context of a method are analogously valid for a device, and vice versa.

[0034] 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.

30 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.

[0035] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element includes a reference to one or more of the features or elements.

[0036] In the context of various embodiments, the phrase “at least substantially” may include “exactly” and a reasonable variance.

[0037] 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.

10 [0038] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0039] Various embodiments may relate to a piezoelectric micromechanical structure for infrared (IR) detection and thermal imaging. Various embodiments may also relate to rugged electronic high pressure / high temperature devices.

15 [0040] Various embodiments may provide an acoustic wave sensor or a surface excited acoustic wave (SEAW) sensor as microbolometer. Various embodiments may include acoustic wave (AW) sensors for microbolometers.

[0041] Various embodiments may provide a detector with a surface excited acoustic wave (SEAW) resonator, and a method of forming the same, that are CMOS compatible.

20 [0042] Various embodiments may provide a piezoelectric micromechanical structure for infrared (IR) detection and thermal imaging. By using electrodes on the top side of an aluminium nitride (AlN) based resonator structure, a surface excited acoustic wave (SEAW) may be generated, which shows a dependency of resonance frequency shift due to far infrared (FIR) light. With a bolometer-like structure, FIR light may be absorbed and a readout of the resulting resonance frequency shift may be possible.

25 [0043] Various embodiments may provide a CMOS-compatible piezoelectric IR sensor with a high temperature coefficient of frequency (TCF), and/or generate acoustic waves with high quality factor, and/or require a vacuum package, and/or provide the ability to adjust resonant frequency by changing the geometry of the electrode layer of the sensor.

30 [0044] Various embodiments may provide a piezoelectric acoustic wave sensor with top electrode layers for IR detection. The sensor may sense a resonance frequency shift that

may indicate a temperature change. The sensor may have no, or at least minimal, 1/f-noise due to high frequencies, and/or no, or at least minimal, self heating.

[0045] Various embodiments may incorporate specific electrodes, for example in terms of design, with surface excited acoustic wave (SEAW) / lateral field excitation film bulk acoustic wave resonator (LFE FBAR) pattern to excite various acoustic waves. The detectors of various embodiments require low power and no direct current (DC) bias.

[0046] Various embodiments may be employed in various applications relating to microbolometers, IR sensors, thermal imaging and mass sensors.

[0047] As compared to conventional devices or film bulk acoustic wave resonator (FBAR) IR sensors with no thermal isolation and with detection only possible for near infrared application (780nm), the detector of various embodiments may include one or more of the following : (1) frequency change of a surface excited acoustic wave (SEAW) may be measured, rather than phase change; (2) tuning of the temperature coefficient of frequency (TCF); (3) a bolometer-like structure; (4) detection of far infrared (FIR) using a bolometer-like structure; (5) thermally isolated, where the thermal isolation may provide an approach to integrate the signal and define a readout time; (6) use of surface acoustic waves (SAW) or surface excited acoustic waves (SEAW); (7) a Fabry Perot IR (or FIR)-absorption structure; or (8) an optimized structure for thermal stress.

[0048] FIG. 1A shows a schematic block diagram of a detector 100, while FIGS. 1B and 1C respectively show cross-sectional representations of the detector 100 of the embodiment of FIG. 1A, according to various embodiments. The detector 100 includes a surface excited acoustic wave (SEAW) resonator 102 including a pair of electrodes 104 and a piezoelectric material 106, the piezoelectric material 106 being electrically coupled to the pair of electrodes 104, the SEAW resonator 102 configured to generate a surface excited acoustic wave, and a substrate 108, wherein the SEAW resonator 102 and the substrate 108 are spaced apart from each other by a gap, and wherein the detector 100 is configured to determine a frequency shift of the surface excited acoustic wave in response to an electromagnetic signal incident on the detector 100. The line represented as 110 is illustrated to show the relationship between the pair of electrodes 104 and the piezoelectric material 106, which may include electrical coupling and/or mechanical

coupling, while the line represented as 112 is illustrated to show the relationship between the SEAW resonator 102 and the substrate 108, which may include electrical coupling and/or mechanical coupling and/or optical coupling.

[0049] In other words, the detector 100 includes a SEAW resonator 102 which may generate a surface excited (or enhanced) acoustic wave having a resonance frequency. The SEAW resonator 102 may include a pair of electrodes 104, for example having a first electrode and a second electrode. The SEAW resonator 102 may further include a piezoelectric material 106 electrically coupled to the pair of electrodes 104. The detector 100 may further include a substrate (e.g. silicon (Si) substrate) 108 which may be spaced apart from the SEAW resonator 102 by a gap (e.g. air gap), which may include any type of optical coupling. When an electromagnetic signal is incident on the detector 100, for example incident on the pair of electrodes 104, the resonance frequency of the surface excited acoustic wave generated may shift, and the detector 100 may determine the frequency (e.g. resonance frequency) shift.

[0050] In the context of various embodiments, the term “surface excited acoustic wave” may mean an acoustic wave traveling along a surface of a material exhibiting elasticity, for example a piezoelectric material, with an amplitude that typically decays exponentially with depth into the material. The acoustic wave may be generated by electrodes (e.g. interdigitated (IDT) electrodes) arranged on the surface of the material exhibiting elasticity. As the acoustic wave propagates within the material, any changes to the characteristics of the propagation path may affect the velocity and/or amplitude of the wave. In the context of various embodiments, the term “surface excited acoustic wave” may include all kinds of acoustic waves which are generated on only one surface. In the context of various embodiments, the term “surface excited acoustic wave” may include an acoustic wave which may be in any mode of vibration, including surface acoustic wave (SAW), film bulk acoustic wave, plate wave, and so on.

[0051] In the context of various embodiments, the wavelength of the surface excited acoustic wave, and therefore its associated frequency, may be determined by the period of the pair of electrodes 104. In various embodiments, the period of the pair of electrodes 104 may be defined by a lithography process.

[0052] In the context of various embodiments, the term “resonator” may mean a device or a system that exhibits resonance, where the device may oscillate or resonate at relatively larger amplitudes at particular frequencies, known as its resonant frequencies, compared to the amplitudes of the oscillations at non-resonant frequencies. A resonator
5 may be used to excite or generate waves such that a surface excited acoustic wave resonator may be used to generate surface excited acoustic waves in a medium. In various embodiments, the pair of electrodes 104 and the piezoelectric material 106 may form a resonating microstructure where the piezoelectric material 106 may be electrically coupled to the pair of electrodes 104 such that the pair of electrodes 104 may excite an
10 acoustic wave to propagate within the piezoelectric material 106.

[0053] In the context of various embodiments, the term “piezoelectric material” may mean a material that may induce electrical charges in response to an applied force or stress or that an applied electric field may cause a change in the dimension of the material. The piezoelectric material may function as a surface excited acoustic wave
15 medium. The piezoelectric material may be in the shape of a square, a rectangle or a circle. However, it should be appreciated that the piezoelectric material may be in any shape or form.

[0054] In the context of various embodiments, the term “electromagnetic signal” may include infrared, for example far infrared (FIR).

[0055] In the context of various embodiments, the piezoelectric material 106 may be electrically coupled to the pair of electrodes 104 such that the pair of electrodes 104 may excite or generate a surface excited acoustic wave to propagate within the piezoelectric material 106. In this context, the term “electrically coupled” may mean that the piezoelectric material 106 is in electrical communication with the pair of electrodes 104
20 such that an electrical current flowing through the pair of electrodes 104 (or an electrical voltage applied to the pair of electrodes 104) may cause an effect (e.g. deformation) on the piezoelectric material 106, for example generating a surface excited acoustic wave to propagate within the piezoelectric material 106. In various embodiments, the resonant frequency of the SEAW resonator 102, and thereof that of the surface excited acoustic
25 wave generated, may be determined based on the geometrical arrangement of the pair of electrodes 104.
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[0056] In the context of various embodiments, the SEAW resonator 102 and the substrate 108 may be spaced apart from each other by a gap. This may mean that the SEAW resonator 102 may be at least substantially arranged to levitate, float or be suspended at a distance from the substrate 108, for example on or above the substrate 108, with a gap in between. This may minimise energy (e.g. thermal energy) loss through the substrate 108, thereby providing a thermal isolation effect between the SEAW resonator 102 and the substrate 108.

[0057] In the context of various embodiments, the gap between the SEAW resonator 102 and the substrate 108 may be in a range of between about 0.25 μm and about 4 μm , for example between about 0.25 μm and about 2.5 μm , between about 0.25 μm and about 1 μm , between about 1 μm and about 2.5 μm , between about 2.5 μm and about 4 μm , or between about 1 μm and about 2 μm . However, it should be appreciated that the gap may be of a value at least substantially equal to the quarter wavelength of the electromagnetic signal to be detected such that a Fabry-Perot optical cavity may be formed. As a non-limiting example, for the detector 100 to absorb an electromagnetic signal with a 10 μm wavelength, the gap between the SEAW resonator 102 and the substrate 108 may be approximately 2.5 μm .

[0058] In the context of various embodiments, the substrate 108 may include one or more CMOS circuits.

[0059] In various embodiments, the detector 100 may further include at least one support structure (e.g. leg structure) arranged to couple to the substrate 108 and the SEAW resonator 102 such that the SEAW resonator 102 may be suspended over the substrate 108.

[0060] In various embodiments, the detector 100 may further include two support structures (e.g. leg structures) arranged to couple to the substrate 108 and the SEAW resonator 102 at a first position and a second position of the SEAW resonator 102 such that the SEAW resonator 102 may be suspended over the substrate 102. This may mean that a first support structure may be coupled to the SEAW resonator 102 at a first position thereof, while a second support structure may be coupled to the SEAW resonator 102 at a second position thereof, where the first support structure and the second support structure may also be coupled to the substrate 108. The first position and

the second position each may include an edge region or side region of the SEAW resonator 102, where the second position may be located opposite to the first position.

[0061] In various embodiments, the at least one support structure may be made of a material having a thermal conductivity lower than respective thermal conductivities of the substrate 108 and the piezoelectric material 106 so as to provide thermal isolation
5 between the SEAW resonator 102 and the substrate 108.

[0062] In the context of various embodiments, the at least one support structure may be made of silicon oxide (SiO_2) or titanium nitride (TiN). The thermal conductivities of SiO_2 and TiN are approximately 1.4 W/m*K and 16 W/m*K, respectively, being
10 comparatively lower than that of the detector (or bolometer) membrane, which may be the piezoelectric material 106 (e.g. made of aluminium nitride (AlN) having a thermal conductivity of 180 W/m*K).

[0063] In various embodiments, the at least one support structure may be of a layer thinner as compared to the thickness of the membrane (or the piezoelectric material 106)
15 to increase the thermal isolation effect between the SEAW resonator 102 and the substrate 108.

[0064] In the context of various embodiments, the piezoelectric material 106 may be aluminium nitride (AlN), zinc oxide (ZnO), lead zirconate titanate (PZT), quartz (SiO_2), aluminum gallium arsenide (AlGaAs), gallium arsenide (GaAs), silicon carbide (SiC),
20 langasite (LGS), gallium nitride (GaN), lithium tantalate (LiTaO_3), lithium niobate (LiNbO_3), polyvinylidene fluoride (PVDF) or any other materials that exhibit piezoelectricity effect.

[0065] In the context of various embodiments, the piezoelectric material 106 may have a length of between about 17 μm and about 180 μm , for example between about 17 μm and
25 about 150 μm , between about 17 μm and about 100 μm , between about 17 μm and about 50 μm , between about 50 μm and about 180 μm , or between about 50 μm and about 100 μm .

[0066] In the context of various embodiments, the piezoelectric material 106 may have a width of between about 17 μm and about 180 μm , for example between about 17 μm and
30 about 150 μm , between about 17 μm and about 100 μm , between about 17 μm and about

50 μm , between about 50 μm and about 180 μm , or between about 50 μm and about 100 μm .

[0067] In the context of various embodiments, the piezoelectric material 106 may have a thickness of between about 0.1 μm and about 3.0 μm , for example between about 0.1 μm and about 2.0 μm , between about 0.1 μm and about 1.0 μm , between about 1.0 μm and about 3.0 μm , or between about 1.0 μm and about 2.0 μm .

[0068] In various embodiments, the detector 100 may further include a material disposed over a surface of the SEAW resonator 102, wherein the material may have a thermal expansion coefficient different from that of the SEAW resonator 102. Therefore, the said material and the SEAW resonator 102 may have a mismatch in their respective thermal expansion coefficients. As a result, stress may be generated in the said material and/or the SEAW resonator 102 in response to a change in temperature.

[0069] In various embodiments, said material may form a ring over the surface of the SEAW resonator 102. The surface of the SEAW resonator 102 over which the material may be disposed may face towards a surface of the substrate 108.

[0070] In various embodiments where the ring formed by said material may be positioned on top of the SEAW resonator (or the bolometer) 102, the temperature coefficient of frequency (TCF) of the SEAW resonator 102 may increase.

[0071] In various embodiments where the ring formed by said material may be positioned on the bottom of the SEAW resonator (or the bolometer) 102, the temperature coefficient of frequency (TCF) of the SEAW resonator 102 may decrease, as the ring may provide a good compensation of the TCF of the SEAW resonator 102, and thereby rendering the detector 100 useful as a reference bolometer.

[0072] In the context of various embodiments, the term “temperature coefficient of frequency” and its acronym “TCF” may provide an indication of the change in frequency corresponding to a change in temperature.

[0073] In the context of various embodiments, the material disposed over a surface of the SEAW resonator 102 may include, but not limited to, aluminum (Al), or titanium nitride (TiN), or titanium (Ti), or tantalum nitride (TaN), or other materials with a high thermal expansion coefficient and which may be CMOS compatible.

[0074] In various embodiments, the pair of electrodes 104 may be arranged in a first layer and the piezoelectric material 106 may form a second layer adjacent to the first layer. This may mean that the pair of electrodes 104 and the piezoelectric material 106 may be arranged one over the other, for example the pair of electrodes 104 may be arranged on or over the piezoelectric material 106. In various embodiments, the second layer may be located between the first layer and the substrate 108.

[0075] In various embodiments, each of the pair of electrodes 104, for example the first electrode and the second electrode, may include a plurality of teeth or fingers. This may mean that each electrode (e.g. the first electrode and the second electrode) of the pair of electrodes 104 may have a comb-shaped like arrangement. The comb structures of the pair of electrodes 104 may enable surface acoustic wave (SAW) and/or lateral field excited film bulk acoustic-wave resonator (LFE-FBAR) wave excitation.

[0076] In the context of various embodiments, the wavelength of the surface excited acoustic wave, and therefore its associated frequency, may be determined by the period or distance between two successive teeth of one electrode, where a tooth of the other electrode may be arranged therebetween.

[0077] In the context of various embodiments, each electrode of the pair of electrodes 104 may have a plurality of teeth in a range of between about 2 teeth and 100 teeth, for example between about 2 teeth and 50 teeth, between about 2 teeth and 20 teeth, between about 20 teeth and 100 teeth, between about 50 teeth and 100 teeth, or between about 30 teeth and 60 teeth.

[0078] In the context of various embodiments, each electrode of the pair of electrodes 104 may have a thickness in a range of between about 5 nm and about 200 nm, for example between about 5 nm and about 100 nm, between about 5 nm and about 50 nm, between about 50 nm and about 200 nm, or between about 100 nm and about 200 nm.

[0079] In various embodiments, the pair of electrodes 104 may be arranged in an interleaving structure. This may mean that an electrode of the pair of electrodes 104 may be arranged one after the other.

[0080] In various embodiments, the pair of electrodes 104 may be arranged in an interdigitated (IDT) structure or a concentric pattern. In the context of various

embodiments, the pair of electrodes 104 may be arranged in an interdigitated pattern or structure to provide one dimensional propagation of the surface excited acoustic wave (SEAW), or concentric-circular patterns to provide two dimensional propagation of the surface excited acoustic wave (SEAW). In various embodiments, the surface excited
5 acoustic wave (SEAW) generated may have a pattern that substantially resembles or substantially similar to the pattern or structure or arrangement of the pair of electrodes 104, such as that arranged in the interdigitated pattern or the concentric-circular pattern.

[0081] For the interdigitated (IDT) structure, the pair of electrodes 104 may be arranged
10 such that each tooth of the plurality of teeth of one electrode (e.g. first electrode) may be alternately arranged with each tooth of the plurality of teeth of the other electrode (e.g. second electrode). For the concentric pattern, the pair of electrodes 104 may be arranged alternately in a concentric pattern, for example a concentric circular pattern.

[0082] In various embodiments, the detector 100 may further include a wave reflector
15 (e.g. an IR reflector) arranged between the SEAW resonator 102 and the substrate 108 to form a Fabry-Perot like structure. This may mean that a Fabry-Perot like structure may be formed by the wave reflector and the SEAW resonator 102. The wave reflector may enhance absorption of the electromagnetic signal.

[0083] In the context of various embodiments, the detector 100 may include one or more
20 release holes, which may help to prevent or at least minimise excessive loss of acoustic wave energy from the piezoelectric material 106 towards the substrate 108.

[0084] In the context of various embodiments, the detector 100 may be or may include an infrared (IR) detector or a far infrared (FIR) detector.

[0085] In the context of various embodiments, the detector 100 may be a bolometer or a
25 microbolometer. As a non-limiting example, the detector 100 may be a CMOS compatible microbolometer.

[0086] In the context of various embodiments, the frequency shift of the surface excited
acoustic wave (SEAW) may include a frequency shift in a resonance frequency, the resonance frequency being defined by a distance or period between the pair of electrodes.

30 This may mean that the detector 100 may determine a resonance frequency shift of the

surface excited acoustic wave in response to an electromagnetic signal incident on the detector 100.

[0087] In the context of various embodiments, the SEAW resonator 102 may include for example LFE-FBAR (Lateral Field Excited Film Bulk Acoustic-Wave Resonator). In various embodiments, the SEAW resonator 102 may excite a surface excited acoustic wave (SEAW), which includes but is not limited to the following waves, for example, surface acoustic wave (SAW), LFE-FBAR mode, Checker-Mode, or any wave that may be excited through electrodes on one surface, for example a surface of the piezoelectric material 106. In the context of various embodiments, the pair of electrodes 104 may be provided on only one surface. This may generate a surface excited acoustic wave (SEAW) on only one surface.

[0088] In the context of various embodiments, the pair of electrodes 104 may be made of a metal, for example including but not limited to, aluminum (Al), gold (Au), molybdenum (Mo), titanium (Ti) or tungsten (W).

[0089] In the context of various embodiments, the terms “couple” and “coupled” may include electrical coupling and/or mechanical coupling.

[0090] In the context of various embodiments, the terms “couple” and “coupled” with regard to two or more components may include direct coupling and/or indirect coupling. For example, two components being coupled to each other may mean that there is a direct coupling path between the two components and/or there is an indirect coupling path between the two components, e.g. via one or more intervening components (e.g. resistor and/or inductor and/or capacitor) connected therebetween.

[0091] Various embodiments may provide a high temperature stable CMOS compatible surface excited acoustic wave (SEAW) sensor with a far infrared (FIR) optimized absorption structure, wherein the readout may be high frequency based, for example up to approximately 2 GHz. A surface excited acoustic wave (SEAW) refers to an acoustic wave mode that is generated by electrodes on only one surface of the sensor, for example such as surface acoustic wave (SAW), lateral field excited film bulk acoustic-wave resonator (LFE-FBAR) wave, checker mode, etc..

[0092] FIG. 2A shows a schematic perspective view of a detector or microbolometer (e.g. a surface excited acoustic wave (SEAW) detector) 200, according to various

embodiments. The detector 200 may include a surface excited acoustic wave (SEAW) resonator 201 including a pair of electrodes (e.g. Al electrodes or TiN electrodes), in the form of a first electrode 202a and a second electrode 202b, and a piezoelectric material or layer 203 which may be electrically coupled to the first electrode 202a and the second electrode 202b. The piezoelectric material 203 may have a rectangular shape. An acoustic wave (e.g. SEAW) may be generated by applying an electric field on the top electrodes, i.e. the first electrode 202a and the second electrode 202b arranged on top of the piezoelectric material 203 or arranged on a top surface of the piezoelectric material 203. As non-limiting examples, the piezoelectric material 203 may be aluminium nitride (AlN), zinc oxide (ZnO), or lithium niobate (LiNbO₃).

[0093] The first electrode 202a may have a plurality of teeth (or fingers), for example as represented by 204a for two teeth, and the second electrode 202b may have a plurality of teeth (or fingers), for example as represented by 204b for two teeth. The first electrode 202a and the second electrode 202b may form an interdigitated (IDT) pattern or configuration, as illustrated within the oval 206, such that a tooth 204a of the first electrode 202a may be arranged alternately with a tooth 204b of the second electrode 202b.

[0094] The distance between the first electrode 202a and the second electrode 202b may define the resonance frequency of the resonator, and therefore the surface excited acoustic wave (SEAW) that may be generated. For example, the distance or spacing between two adjacent teeth 204a of the first electrode 202a, and/or the distance or spacing between two adjacent teeth 204b of the second electrode 202b, may define the resonance frequency.

[0095] The SEAW resonator 201 may include a first wave reflector 208a and a second wave reflector 208b arranged on opposite edge regions of the SEAW resonator 201. The first wave reflector 208a and the second wave reflector 208b may cooperate to reflect at least a portion of an acoustic wave (e.g. a surface excited acoustic wave (SEAW)) that may be generated by the IDT electrodes 206.

[0096] The first electrode 202a and the second electrode 202b may act as an infrared (IR)-absorption layer as well as a contact layer.

[0097] The detector 200 may include two support structures, in the form of bolometer legs, e.g. a first bolometer leg 210a and a second bolometer leg 210b arranged on opposite edge regions of the SEAW resonator 201. The first bolometer leg 210a may be coupled to a first anchor structure 212a, while the second bolometer leg 210b may be coupled to a second anchor structure 212b. The first anchor structure 212a and the second anchor structure 212b may be coupled to one or more complementary metal–oxide–semiconductor readout integrated circuits (CMOS ROIC). This may mean that on or more CMOS circuits may be arranged underneath the SEAW resonator 201. Each of the first anchor structure 212a and the second anchor structure 212b may be conductive, for example including a metallic material.

[0098] The detector 200 may include a substrate (not shown) that may be spaced apart from the resonator 201 by a gap (e.g. an air gap) and arranged beneath the resonator 201. Having a gap in between the resonator 201 and the substrate may provide thermal isolation of the resonator 201 from the substrate, which may minimise thermal energy or heat loss from the resonator 201. Therefore, the detector 200 may have a microbolometer like structure to isolate the sensor or resonator 201 from the substrate. The substrate may be coupled to the first anchor structure 212a and the second anchor structure 212b.

[0099] The detector 200 may further include a wave reflector (e.g. an IR reflector) 214 arranged between the SEAW resonator 201 and the substrate to form a Fabry-Perot like structure. The wave reflector 214 may reflect, at least a portion of a wave (e.g. an electromagnetic signal, such as infrared, e.g. far infrared) that may be incident on the resonator 201 towards the resonator 201, the first electrode 202a and the second electrode 202b. This may enhance absorption of the wave. The wave reflector 214 may be arranged on the substrate.

[0100] The sensor or resonator 201 may be thermally isolated from the substrate so that the IR-light (heat) absorbed by the first electrode 202a and the second electrode 202b may cause a rise of temperature within the resonator 201, which may cause a shift of the acoustic wave sensor resonance frequency. In other words, the resonance frequency of the SEAW resonator 201, and accordingly also, the resonance frequency of the SEAW generated, may be changed as a result of a change (e.g. increase) in temperature of the resonator 201 resulting from the absorption of IR light or signal. In various embodiments,

a vacuum package may be provided for the detector 200. Apart from physically spacing the resonator 201 from the substrate by a gap, thermal isolation may also be achieved by using low thermal conductive materials (e.g. SiO₂ or TiN) for the first bolometer leg 210a and the second bolometer leg 210b. As a non-limiting example, the first bolometer leg 210a and the second bolometer leg 210b may be made of a material having a thermal conductivity lower than respective thermal conductivities of the substrate and the piezoelectric material 203. Therefore, in various embodiments, the thermal time constant, τ_{th} , of the detector 200 may be adjusted by varying the thermal conductance, λ_{bolo} , of the first bolometer leg 210a and the second bolometer leg 210b, for example by variation of the geometry and/or the materials of the first bolometer leg 210a and/or the second bolometer leg 210b.

[0101] The acoustic wave (SEAW) itself may be generated by the comb-structured thin electrodes of the first electrode 202a and the second electrode 202b, wherein the distance between the first electrode 202a and the second electrode 202b may define the resonance frequency. Such comb structures may enable surface acoustic wave (SAW) and/or lateral field excited film bulk acoustic-wave resonator (LFE-FBAR) wave excitation. As a non-limiting example, by creating a specific sheet resistance (377 $\Omega/\square$ (ohm/square)), the first electrode 202a and the second electrode 202b may be able to act as an absorption layer for the IR-light at the same time. Together with the underlying IR-reflector 214, for example a highly electrical conductive material (e.g. a metallic material), the absorption layer defined by the first electrode 202a and the second electrode 202b may create a Fabry-Perot like structure, in which the distance between the absorption layer and the IR-reflector 214 may define the maximum absorption wavelength.

[0102] Due to the combed structure of the first electrode 202a and the second electrode 202b, the current flow through the sensor or resonator 201 may be minimized, so that the self heating effect of the microbolometer or detector 200 may become negligible or minimal. At the same time, due to the negligible current flow and the high readout frequency, the 1/f and the thermal noise may be drastically reduced, which provide advantages for acoustic waves IR-sensors, such as the detector 200, as compared to the conventional resistive sensors.

[0103] In various embodiments, it should be appreciated that other electrode configurations may be employed for the detector 200, as shown in FIG. 2B, to excite different modes. FIG. 2B shows a standard interdigitated (IDT) structure 220 for surface acoustic wave (SAW) mode and/or LFE-FBAR mode, which may be similar to the IDT structure 206 of FIG. 2A. The standard IDT structure 220 includes a first electrode 202a with a plurality of teeth 204a, and a second electrode 202b with a plurality of teeth 204b, where a tooth 204a of the first electrode 202a may be arranged alternately with a tooth 204b of the second electrode 202b.

[0104] In various embodiments, electrode patches (e.g. 2, 3, 4 or any higher number of electrode patches) may be arranged along each tooth 204a of the first electrode 202a and each tooth 204b of the second electrode 202b. The electrode patches may be spaced apart from each other. As shown in FIG. 2B, a checker IDT structure 230 for checker mode may be provided. The checker IDT structure 230 may be similar to the standard IDT structure 220, except that a plurality of spaced apart square electrode patches 232 may be arranged along each tooth 204a of the first electrode 202a and each tooth 204b of the second electrode 202b. Therefore, a checker-patterned electrode architecture may be provided. In further embodiments, a diamond IDT structure 240 may be provided, where the diamond IDT structure 240 may be similar to the standard IDT structure 220, except that a plurality of spaced apart diamond-shaped electrode patches 242 may be arranged along each tooth 204a of the first electrode 202a and each tooth 204b of the second electrode 202b.

[0105] Also, a spiral IDT structure 250 may be provided where the first electrode 202a and the second electrode 202b may be arranged in a spiral pattern. The first electrode 202a and the second electrode 202b may be arranged adjacent each other, where a portion of the first electrode 202a and a portion of the second electrode 202b may be arranged alternately. The first electrode 202a and the second electrode 202b may form an interleaving configuration.

[0106] A zigzag IDT structure 260 may instead be provided, for LFE-FBAR mode, where the zigzag IDT structure 260 may be similar to the standard IDT structure 220, except that each tooth 204a of the first electrode 202a and each tooth 204b of the second electrode 202b may have a zigzag-like pattern.

[0107] FIG. 2C shows a schematic top view of a detector (e.g. surface excited acoustic wave (SEAW) detector) 270, according to various embodiments. In a non-limiting example, the detector 270 includes a SEAW resonator 201 having a first electrode 202a with 60 teeth or fingers 204a and a second electrode 202b with 60 teeth or fingers 204b arranged in an IDT configuration, where the first electrode 202a and the second electrode 202b are arranged on a piezoelectric material 203 in the form of a membrane having a diameter of 750 μm ($\varnothing = 750 \mu\text{m}$). The line width of the electrode fingers 204a, 204b may be approximately 5 μm . The detector 270 may include a 10 μm -thick silicon (Si) membrane (not shown) arranged below the piezoelectric material 203. The Si membrane may have a diameter of 750 μm or more. It should be appreciated that a 50 μm -thick silicon (Si) membrane may instead be employed. The detector 270 may further include one or more release holes 272 which may help to prevent or at least minimise excessive loss of acoustic wave energy from the piezoelectric membrane 203 towards the Si substrate or membrane (not shown).

[0108] FIG. 2D shows a partial 3D perspective view of the simulated vibration mode of a radial surface excited acoustic wave sensor 280, according to various embodiments, illustrating the electric potential variation across the IDT electrodes 282 at its resonant frequency of about 243 MHz.

[0109] The fabrication process for forming the detector of various embodiments will now be described by the following non-limiting examples, and with reference to FIGS. 3A to 3K. FIGS. 3A to 3K show, as cross-sectional views, various processing stages or process flow of a method for manufacturing a detector (e.g. SEAW detector), according to various embodiments.

[0110] Referring to FIG. 3A, a substrate (e.g. silicon (Si) substrate) 302 may be provided. Oxide deposition, for example via chemical vapour deposition (CVD), may be carried out to deposit an oxide (e.g. silicon oxide (SiO_2)) 304. The oxide 304 may act as a dielectric layer or a passivation layer. Subsequently, a metallic layer (e.g. aluminum (Al)) may be deposited over the oxide 304 and may be patterned to form contacts 306 and an IR-reflector 305. Therefore, a structure 300 may be obtained.

[0111] Subsequently, a second oxide layer (e.g. silicon oxide (SiO_2), for example via CVD, may be deposited over the IR-reflector 305 and the contacts 306, and which may

act as a dielectric layer or a passivation layer. Amorphous silicon (a-silicon) may then be deposited over the second oxide layer as a sacrificial layer. As shown in FIG. 3B, a structure 310 may be obtained, having a second oxide 312 and a layer of a-silicon 314.

[0112] Referring to FIG. 3C, a third oxide layer (e.g. silicon oxide (SiO_2) 316, for example via CVD, may be deposited over the a-silicon layer 314, followed by deposition of a piezoelectric material (e.g. aluminium nitride (AlN)) 318 over the third oxide layer 316, for example via a sputtering process. Therefore, a structure 320 may be obtained. Thereafter, AlN structuring may be carried out to form the AlN 318, for example into a block structure. A structure 324 may be obtained, as shown in FIG. 3D.

[0113] Referring to FIG. 3E, a further oxide layer (e.g. silicon oxide (SiO_2) 330, for example via CVD, may be deposited over the AlN structure 318 and patterned or structured, for example to form a plurality of strips 330, with a gap 332 in between adjacent oxide strips 330. Therefore, a structure 334 may be obtained.

[0114] Referring to FIG. 3F, subsequently, contact deposition for example via atomic layer deposition (ALD), may be performed to deposit titanium nitride (TiN) 338, which may then be structured to form the TiN material 338 in the gaps 332. Therefore, a structure 340 may be obtained, with TiN contacts 338 which may define a pair of electrodes.

[0115] Oxide deposition may then be carried out, for example via CVD, to deposit an oxide layer (e.g. silicon oxide (SiO_2) over the structure 340, as a passivation layer. As shown in FIG. 3G, a structure 344 may be obtained, with an oxide layer 346 over the TiN contacts 338.

[0116] Referring to FIG. 3H, contact hole etching may be carried out to etch holes or vias 350 through respective portions of the oxide layers 312, 316, 346, a-silicon 314, and TiN 338 so as to expose the Al contacts 306. As a result, a structure 352 may be obtained.

[0117] Metal deposition may then be carried out to deposit a metal layer over the structure 352 and into the vias 350, which may then be structured to remove parts of the metal layer except at portions near the vias 350, and in the interior of the vias 350. As shown in FIG. 3I, a structure 360 may be obtained, with a metal layer 362 formed in each via 350, deposited on the bottom of the via 350 and in contact with the Al contact 306, as

well as on the sidewalls of the via 350 and on a portion of a surface of the oxide layer 346.

[0118] Referring to FIG. 3J, subsequently, geometry forming of the structure 360 may be carried out to remove materials from the structure 360, for example as indicated by 366, so that the AlN material 318 and the TiN contacts 338 may be anchored to the substrate 302 via the support afforded by the metal layer 362 formed in each via 350. Therefore, a structure 370 may be obtained.

[0119] Referring to FIG. 3K, the AlN material 318 and the TiN contacts 338 which may define a resonator 372 may then be released by etching of the a-silicon 314 using xenon difluoride (XeF_2) such that the resonator 372 may be suspended above the substrate 302 at suspension points corresponding to the vias 350 with the metal layer 362, and spaced apart from the substrate 302 by a gap 374. A structure 380 may be obtained, where the resonator 372 may levitate above the substrate 302. The resonator 372 may be arranged on top of the IR-reflector 305, separated by the gap 374.

[0120] The IR detector of various embodiments may be fabricated on CMOS based fabrication line and be maintained as a post-process to the CMOS. The CMOS post-process may include four main steps of (1) deposition and structuring of the AlN sensor layer or piezoelectric material 318 (corresponding to FIG. 3D); (2) contact of the AlN 318 with a thin contact material 338 and structuring the contact material 338 to build the sensor electrodes (corresponding to FIG. 3F); (3) metal deposition for the metal plugs 362, which connect the sensor or resonator 372 to the CMOS and act as a supporting membrane structure at the same time (corresponding to FIG. 3I); and (4) etching of the sacrificial layer (a-silicon 314) to release the suspended membrane (AlN 318) of the microbolometer 380 (corresponding to FIG. 3K).

[0121] The response time of the detector (or microbolometer) of various embodiments will now be described. The response time may refer to the minimum time to be waited for, after an object temperature is changed. By definition, the response time may be reached after more than 3 times of the thermal time constant, τ_{th} , (e.g. $> 3\tau_{th}$) and the signal output becomes 95% of its final value. Furthermore, the thermal time constant τ_{th} may be described by the microbolometer thermal capacity, c_{bolo} , divided by its thermal conductance, λ_{bolo} , as provided by equation 1 below.

$$\tau_{th} = \left(\frac{C_{bolo}}{\lambda_{bolo}} \right) \quad (\text{Equation 1}).$$

[0122] A non-limiting way for estimating the microbolometer thermal time constant, τ_{th} , may be given by

$$T(t) = T_{Sub} + \Delta T \left(1 - e^{-\frac{t}{\tau_{th}}} \right) \quad (\text{Equation 2}),$$

5 where $T(t)$ refers to the time dependant bolometer temperature, T_{Sub} refers to the substrate temperature, and ΔT refers to the temperature rise after exposing the sensor to a heat source.

[0123] The time dependant temperature behavior of the bolometer structure of various embodiments may be simulated using a finite element analysis software, to obtain the thermal time constant, τ_{th} , and the thermal response time. FIG. 4 shows a plot 400 of simulation results 402 for the bolometer temperature against the response time. The results 402 show the simulated time dependant temperature, $T(t)$, against time. For comparison purposes, the theoretical values, represented by the square data points (as indicated by 404 for one data point), are included in the plot 400. By using equation 2, 15 the temperature behaviour may be modelled and the thermal time constant, τ_{th} , may be estimated to be about 7.4 ms, with the thermal response time approximately 22.2 ms.

[0124] Tuning of the temperature coefficient of frequency (TCF) and noise equivalent temperature difference (NETD) estimation for the detector (or microbolometer) of various embodiments will now be described. The temperature dependent frequency shift 20 of a surface excited acoustic wave (SEAW) sensor may be caused by a change of the material elasticity matrix and thermal expansion.

[0125] FIG. 5A shows a scanning electron microscopy image 500 of a detector 502, in partial view, according to various embodiments. The detector 502 includes a piezoelectric material or membrane 504 (e.g. approximately 1 μm -thick AlN layer) arranged over a silicon (Si) layer or substrate of about 10 μm thick, and an IDT structure 506 including a first electrode 508a with a plurality of teeth 510a, and a second electrode 508b with a plurality of teeth 510b arranged on the piezoelectric material 504. Each of the first electrode 508a and the second electrode 508b may be Al electrode which may be about 25

0.2 μm thick, with approximately 5 μm -line width teeth 510a, 510b respectively, and approximately 5 μm -spacing between adjacent teeth 510a, and between adjacent teeth 510b respectively. The detector 502 further includes a wave reflector structure 516 arranged to the side of the IDT structure 506. The detector 502 further includes one or
5 more release holes of approximately 750 μm diameter.

[0126] FIG. 5B shows a plot 530 of frequency shift against temperature for the detector 502 of the embodiment of FIG. 5A. The result shown by the plot 530 illustrates a TCF of approximately -40 ppm/K, where the frequency shift is at least substantially linear due to temperature until about 90°C, and for temperatures beyond 90°C, second
10 order effects may occur.

[0127] FIG. 5C shows a plot 540 of resonance frequency shift for the detector 502 of the embodiment of FIG. 5A for different temperatures. The plot 540 shows the results for temperatures of about 20°C, about 30°C, about 40°C, about 50°C, about 60°C, about 70°C, about 80°C, about 90°C, and about 100°C.

[0128] In various embodiments, by using materials which may have a large mismatch of their respective thermal expansion coefficients relative to each other, it may be possible to increase the temperature coefficient of frequency (TCF) of the IR sensor or resonator of a detector.
15

[0129] As a non-limiting example, the temperature behavior of a radial SEAW sensor, with a 300 nm thick AlN-layer as membrane, and dependant on an Al-ring arranged at the
20 bottom of the resonator, may be simulated, and the results may be as shown in FIG. 6A. As non-limiting examples, for the purpose of simulations for obtaining the results shown in FIGS. 6A to 6D, the AlN-layer may have a radius of about 17 μm and a thickness of about 300 nm, the Al-ring or layer may have a thickness of about 100 nm, while the
25 sensor may also include respective silicon oxide (SiO_2) layers, each SiO_2 layer having a thickness of about 100 nm, above and below the AlN pizeoelectric material layer, and a 2 μm IDT of electrodes (e.g. having 2 μm -line width IDT electrode fingers).

[0130] FIG. 6A shows a 3D perspective view of a simulated radial surface excited acoustic wave sensor 602, illustrating membrane bending in 3D. The membrane 604 of
30 the sensor or resonator 602 includes the same material configuration as described above

in the context of the microbolometer of various embodiments and therefore represents a simplified model for the temperature behavior of the IR-sensor 602.

[0131] FIG. 6B shows a partial cross sectional view of a simulated radial surface excited acoustic wave sensor 610 with a top aluminum (Al) layer 612, according to various
5 embodiments. The sensor 610 includes a stack of SiO₂ layer 614, AlN membrane 616, IDT electrodes 618, SiO₂ layer 620 and an Al layer 612 on top of the membrane 616.

[0132] FIG. 6C shows a partial cross sectional view of a simulated radial surface excited acoustic wave sensor 630 with no aluminum layer or ring, according to various
10 embodiments. The sensor 630 includes a stack of SiO₂ layer 614, AlN membrane 616, IDT electrodes 618 and SiO₂ layer 620.

[0133] FIG. 6D shows a partial cross sectional view of a simulated radial surface excited acoustic wave sensor 640 with a bottom aluminum (Al) ring 642, according to various
embodiments. The sensor 640 includes a stack of SiO₂ layer 614, AlN membrane 616, IDT electrodes 618, SiO₂ layer 620 and an Al ring 642 on the bottom.

15 [0134] As shown in FIGS. 6B to 6D, the AlN membrane 616 of the sensor 610 shows the greatest displacement as compared to the sensor 630 and the sensor 640, with the AlN membrane 616 of the sensor 640 exhibiting minimal displacement.

[0135] FIG. 6E shows a plot 650 of simulation results for the temperature coefficient of frequency (TCF) for respective radial surface excited acoustic wave sensors of the
20 embodiments of FIGS. 6B to 6D. The plot 650 shows the result 652 corresponding to the sensor 610 (FIG. 6B), result 654 corresponding to the sensor 630 (FIG. 6C) and result 656 corresponding to the sensor 640 (FIG. 6D). The simulation result 656 illustrated in plot 650 indicate that a bottom Al-ring may increase the TCF up to -90 ppm/K and therefore increase the sensitivity of the sensor 640. Furthermore, the
25 results illustrated in plot 650 show a dependency of the sensor's TCF towards a mismatch of the respective thermal expansion coefficients of different materials. In addition to the mismatch of the thermal expansion coefficients, the distance change between the pair of electrodes of the IDT electrodes 618 during heating may also contribute to the shift in resonance frequency.

30 [0136] FIG. 6F shows a plot 660 of the frequency shift for the radial surface excited acoustic wave sensor 640 of the embodiment of FIG. 6D for different temperatures. The

plot 660 shows the result 662 for a temperature of 25°C, result 664 for a temperature of 25.1°C, result 666 for a temperature of 25.2°C, result 668 for a temperature of 25.5°C, and result 670 for a temperature of 26°C.

[0137] Assuming a negligible 1/f-noise and the thermal noise of the detector, the major noise contribution may arise from the feedback of the CMOS circuit and the detector. This kind of noise is called phase noise or jitter noise. The period change, Δt , of the jitter noise of a CMOS radio frequency (RF) MEMS circuit may be in the femto second range for frequencies up to about 5 GHz. Equation 3 below may be used to estimate the circuit period change, Δt , of the jitter noise for the microbolometer of various embodiments with a temperature resolution (NETD) of 20 mK.

$$\Delta t = \left[\frac{1}{f_o} \right] - \left[\frac{1}{(f_o + 0.02f_s)} \right] \approx 0.02 \frac{f_s}{(f_o)^2} \quad (\text{Equation 3}),$$

where f_o represents the resonance frequency and f_s represents the sensor sensitivity (ppm/K).

[0138] Assuming a resonance frequency, f_o , of about 1 GHz, the sensor sensitivity may be 90 kHz/K for a TCF of about 90 ppm/K. In equation 3, the factor of 0.02 indicates the 20 mK NETD resolution that is to be reached. Overall, a circuit period change of $\Delta t = 1.5$ fsec may be obtained, which may be a reasonable value for a CMOS readout circuit jitter noise.

[0139] FIG. 7A shows a simulated temperature distribution of a detector 700, according to various embodiments. The result shows that the temperature at the resonator 702 may be highest, where the temperature may decrease moving in a direction from the portion of each leg 704 coupled to the resonator 702 towards the end portion 706 of each leg 704.

[0140] FIG. 7B shows a plot 720 of time dependent thermal behavior of the detector 700 of FIG. 7A, illustrating the temperature variation at the centre portion of the resonator 702 with time.

[0141] The result as shown in plot 720 may be based on the relationship below which describes when an infrared (IR) source may be turned ON and OFF

$$\text{Radiation}_{\text{Power}} * \text{Rect}(t) = \text{Radiation}_{\text{Power}} * 0.5 * (\text{SIGN}(t - 0.001) - \text{SIGN}(t - 0.025)) \quad (\text{Equation 4}),$$

where $\text{Radiation}_{\text{power}}$ represents the IR source power, $\text{Rect}(t)$ represents the pulse function, SIGN represents the sign function, and t represents time.

[0142] Measurement results of the detectors of various embodiments will now be described. Detectors may be fabricated based on the embodiments of FIGS. 8A to 8D.

5 FIG. 8A shows a schematic top view of a detector 800 having a surface excited acoustic wave (SEAW) resonator 802 fixed on four coupling sites, for example at the top edge 804a and at the bottom edge 804b, and at the right suspension point 804c and at the left suspension point 804d., coupled to the substrate (not shown). The resonator 802 may be stable fixed on the top, via coupling site 804a, and bottom, via coupling site 804b, and
10 semi-fixed on the right, via suspension point 804c and on the left, via suspension point 804d. The term “stable fixed” may mean being fixed by an edge, while the term “semi-fixed” may mean being fixed by a suspension point. It should be appreciated that the term “suspension point” may mean a site which may allow a component coupled to the suspension point to move or flex at the suspension point, meaning that the
15 “suspension point” may act as a pivot point. The resonator 802 includes an IDT structure 806 made up of a first comb-shaped electrode 808a and a second comb-shaped electrode 808b, on a 1 μm thick AlN sensor layer 803. The first comb-shaped electrode 808a may be electrically coupled to a plurality of contact pads 810 while the second comb-shaped electrode 808b may be electrically coupled to a plurality of contact
20 pads 812. The detector 800 may include a plurality of release holes 816 adjacent the resonator 802. The detector 800 may be labelled as “FSAW11”.

[0143] FIG. 8B shows a schematic top view of a detector 820 having a surface excited acoustic wave (SEAW) resonator 802 fixed on six coupling sites at six suspension points, for example two suspension points 804a, 804e on the top side, two suspension
25 points 804b, 804f at the bottom side, a suspension point 804c on the right side, and a suspension point 804d on the left side, coupled to the substrate (not shown). The detector 820 may be similar to the detector 800 (FIG. 8A), except that the resonator 802 may also be semi fixed on the top and bottom. The detector 820 may be labelled as “FSAW14”.

30 [0144] FIG. 8C shows a schematic top view of a detector 830 having a surface excited acoustic wave (SEAW) resonator 802 fixed on two coupling sites, for example at the

right edge 804c and at the left edge 804d, coupled to the substrate (not shown). Therefore, the resonator 802 may be stable fixed on the left and on the right. The resonator 802 includes an IDT structure 806 made up of a first comb-shaped electrode 808a and a second comb-shaped electrode 808b, on a 1 μ m thick AlN sensor layer 803. The first comb-shaped electrode 808a may be electrically coupled to a plurality of contact pads 810 while the second comb-shaped electrode 808b may be electrically coupled to a plurality of contact pads 812. The detector 830 may include a plurality of release holes 816 adjacent the resonator 802. The detector 830 may be labelled as "FSAW17".

[0145] FIG. 8D shows a schematic top view of a detector 840 having a surface excited acoustic wave (SEAW) resonator 802 fixed on two coupling sites, for example at the right suspension point 804c and at the left suspension point 804d, coupled to the substrate (not shown). Therefore, the resonator 802 may be semi fixed on the left and on the right. The resonator 802 includes an IDT structure 806 made up of a first comb-shaped electrode 808a and a second comb-shaped electrode 808b, on a 1 μ m thick AlN sensor layer 803. The first comb-shaped electrode 808a may be electrically coupled to a plurality of contact pads 810 while the second comb-shaped electrode 808b may be electrically coupled to a plurality of contact pads 812. The detector 840 may include a plurality of release holes 816 adjacent the resonator 802. The detector 840 may be labelled as "CMR12".

[0146] In order to estimate the temperature behaviour of the microbolometers of various embodiments, temperature measurements may be performed based on the SEAW resonator 802 of the embodiments of FIGS. 8A to 8D. The SEAW resonator 802 may have similarities to the microbolometers of various embodiments regarding suspension and electrode configuration.

[0147] Temperature measurement may be performed on a heated chuck and the respective detectors 800, 820, 830, 840 may be contacted with two ground-signal-ground (GSG) probes in order to measure the S12 behavior of the SEAW resonator 802. Measurements may be carried out with a network analyzer, in which the resonance frequency of the resonator 802 is about ~770 MHz.

[0148] FIG. 8E shows a plot 840 of the temperature coefficient of frequency (TCF) for the surface excited acoustic wave detectors 800, 820, 830, 840, of the embodiments of FIGS. 8A to 8D respectively. The plot 840 shows the result 852 for the "FSAW11" detector 800, result 854 for the "FSAW14" detector 820, result 856 for the "FSAW17" detector 830, and result 858 for the "CMR12" detector 840. The TCF may vary, rather than remain constant, as a result of the thermal instability of the heated chuck.

[0149] FIG. 8F shows a plot 860 derived from the plot 840 for the surface excited acoustic wave detectors 830, 840, expanded in the range of temperature between about 25°C and about 105°C. The initial stress, which may be caused by the mismatch of the coefficient of thermal expansions of the sensor material or the sensor suspension, may change the temperature behavior of the sensor 802 and therefore the TCF. Due to the instability of the heated chuck, the TCF results 856, 858, do not remain constant for both "FSAW17" detector 830 and "CMR12" detector 840 respectively. Nevertheless, the result 858 shows that the "CMR12" detector 840 exhibits a much lower TCF of about -30 ppm/K, compared to the TCF of the "FSAW17" detector 830 of about -45 ppm/K.

[0150] As shown in FIGS. 8E and 8F, the "CMR12" detector 840 shows a lower response on temperature as compared to the other detectors 800, 820, 830, illustrating the TCF dependency on the design of the resonator or sensor 802. Therefore, using different suspension designs and materials with a huge mismatch of their respective coefficient of thermal expansions may lead to a significant increase of the TCF and therefore to a higher sensitivity of the sensor 802.

[0151] Investigation on the TCF released SAW structures of the four different detectors 800, 820, 830, 840 may be carried out based on the four respective designs as described above for SAW based IR-sensors, using different suspension / initial stress. As a non-limiting example, the result for the shift of resonance frequency due to temperature for the "FSAW14" detector (S12 measurement) is as shown in FIG. 8G.

[0152] FIG. 8G shows a plot 870 of resonance frequency shift for the detector 820 of the embodiment of FIG. 8B for different temperatures. The plot 870 shows the results for temperatures of about 20°C, about 30°C, about 40°C, about 50°C, about 60°C, about 70°C, about 80°C, about 90°C, and about 100°C.

[0153] FIG. 9A shows a plot 900 of minimal log magnitude against temperature, according to various embodiments, for example based on the embodiment of the detector 502 of FIG. 5A. Plot 900 shows the measured result 902 and a fitted line 904 having a relationship of $y = -0.0128x - 7.7502$. Plot 900 shows that the minimal magnitude increases on increasing temperature.

[0154] FIG. 9B shows a plot 920 of temperature coefficient of frequency (TCF) against temperature, according to various embodiments, for example based on the embodiment of the detector 502 of FIG. 5A, illustrating a TCF of approximately -40 ppm/K for temperatures up to about 90°C, and which then increase, in terms of magnitude, for temperatures above 100°C.

[0155] Various embodiments may provide a high temperature stable CMOS compatible surface excited acoustic wave microbolometer, which may have a low 1/f noise and thermal noise. Due to the negligible current flow through the sensor or resonator, the self heating effect may be minimized. By using a thermally isolated structure, it may be possible to enhance the heat confinement within the membrane or piezoelectric material, thereby increasing the sensor sensitivity. In order to optimize the IR-light absorption for a specific wavelength, a Fabry-Perot like structure may be included for the microbolometer design. Furthermore, tuning of the sensor's TCF may be achieved by using materials with mismatched coefficient of thermal expansions.

[0156] Based on the above, the detectors of various embodiments may include one or more of the following: (1) use of piezoelectric material for far infrared (FIR) detection; (2) use of acoustic wave (e.g. SEAW) for FIR sensing; (3) use of resonance frequency shift for detecting FIR light; (4) use of thermal expansion and change of the material elasticity matrix, for example for facilitating resonance frequency shift; (5) use of extreme temperature stable material (e.g. for up to 300°C), thereby resulting in more reliable packaging; (6) extreme fast read out time; (7) minimization of 1/f-noise due to high frequencies; (8) reduction of the self heating effect due to low power demands of the detector; (9) a high temperature packaging method for the detector; or (10) a temperature dependency approach for acoustic wave pressure sensor. The detectors of various embodiments may provide a highly selective resonance mode for temperature detection, and/or a large operation frequency range from MHz to GHz.

[0157] Various embodiments of the detectors or uncooled IR bolometers may be designed to include one or more of the following parameters: (1) a bolometer type structure incorporating titanium nitride (TiN) / aluminium nitride (AlN); (2) an array format of approximately 320×240 pixels or 640×480 pixels; (3) a power dissipation of
5 < 100 mW; (4) a pixel pitch of about 25 μm ; (5) a noise equivalent temperature difference (NETD) of < 20 mK; (6) an operating temperature of between about -40°C to about $+300^\circ\text{C}$; (7) a spectral bandwidth of between about 8 μm and about 12 μm ; or (8) a frame rate of about 30 Hz.

[0158] It should be appreciated that modifications to the detector of various embodiments
10 may be carried out to provide a surface acoustic wave (SAW) or surface excited acoustic wave (SEAW) sensor for high MHz – GHz range, and/or to provide or improve on the thermal isolation of the IR-detectors, and/or to provide improvements in design to increase the temperature coefficient of frequency (TCF) and quality factor (Q) for IR detection applications.

[0159] While the invention has been particularly shown and described with reference to
15 specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning
20 and range of equivalency of the claims are therefore intended to be embraced.

CLAIMS

1. A detector comprising:
 - a surface excited acoustic wave (SEAW) resonator comprising a pair of electrodes
 - 5 and a piezoelectric material, the piezoelectric material being electrically coupled to the pair of electrodes, the SEAW resonator configured to generate a surface excited acoustic wave; and
 - a substrate,
 - wherein the SEAW resonator and the substrate are spaced apart from each
 - 10 other by a gap; and
 - wherein the detector is configured to determine a frequency shift of the surface excited acoustic wave in response to an electromagnetic signal incident on the detector.
- 15 2. The detector of claim 1, further comprising at least one support structure arranged to couple to the substrate and the SEAW resonator such that the SEAW resonator is suspended over the substrate.
3. The detector of claim 1, further comprising two support structures arranged to
- 20 couple to the substrate and the SEAW resonator at a first position and a second position of the SEAW resonator such that the SEAW resonator is suspended over the substrate.
4. The detector of claim 3, wherein the first position and the second position each comprises an edge region or side region of the SEAW resonator, the second position
- 25 being located opposite to the first position.
5. The detector of any one of claims 2 to 4, wherein the at least one support structure is made of a material having a thermal conductivity lower than respective thermal conductivities of the substrate and the piezoelectric material to provide thermal isolation
- 30 between the SEAW resonator and the substrate.

6. The detector of any one of claims 2 to 5, wherein the at least one support structure is made of SiO₂ or TiN.

7. The detector of any one of claims 1 to 6, wherein the piezoelectric material is
5 selected from the group consisting of aluminum nitride (AlN), zinc oxide, lead zirconate titanate, quartz, aluminum gallium arsenide, gallium arsenide, silicon carbide, langasite, gallium nitride, lithium tantalite, lithium niobate and polyvinylidene fluoride.

8. The detector of any one of claims 1 to 7, further comprising a material disposed
10 over a surface of the SEAW resonator, wherein the material has a thermal expansion coefficient different from that of the SEAW resonator.

9. The detector of claim 8, wherein the material forms a ring over the surface of the SEAW resonator.

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10. The detector of claim 8 or 9, wherein the surface of the SEAW resonator over which the material is disposed faces towards a surface of the substrate.

11. The detector of any one of claims 8 to 10, wherein the material comprises
20 aluminum, or TiN, or Ti, or TaN.

12. The detector of any one of claims 1 to 11, wherein the pair of electrodes is arranged in a first layer and the piezoelectric material forms a second layer adjacent to the first layer.

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13. The detector of claim 12, wherein the second layer is located between the first layer and the substrate.

14. The detector of any one of claims 1 to 13, wherein each of the pair of electrodes
30 comprises a plurality of teeth.

15. The detector of any one of claims 1 to 14, wherein the pair of electrodes is arranged in an interleaving structure.

16. The detector of any one of claims 1 to 15, wherein the pair of electrodes is
5 arranged in an interdigitated structure or a concentric pattern.

17. The detector of any one of claims 1 to 16, further comprising a wave reflector arranged between the SEAW resonator and the substrate to form a Fabry-Perot like structure.

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18. The detector of any one of claims 1 to 17, wherein the detector comprises an infrared (IR) detector or a far infrared (FIR) detector.

19. The detector of any one of claims 1 to 18, wherein the detector is a
15 microbolometer.

20. The detector of any one of claims 1 to 19, wherein the detector is a CMOS compatible microbolometer.

20 21. The detector of any one of claims 1 to 20, wherein the frequency shift of the surface excited acoustic wave comprises a frequency shift in a resonance frequency, the resonance frequency being defined by a distance between the pair of electrodes.