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(54) **GAS PHASE CHEMICAL SENSOR BASED ON FILM BULK RESONATORS (FBAR)**

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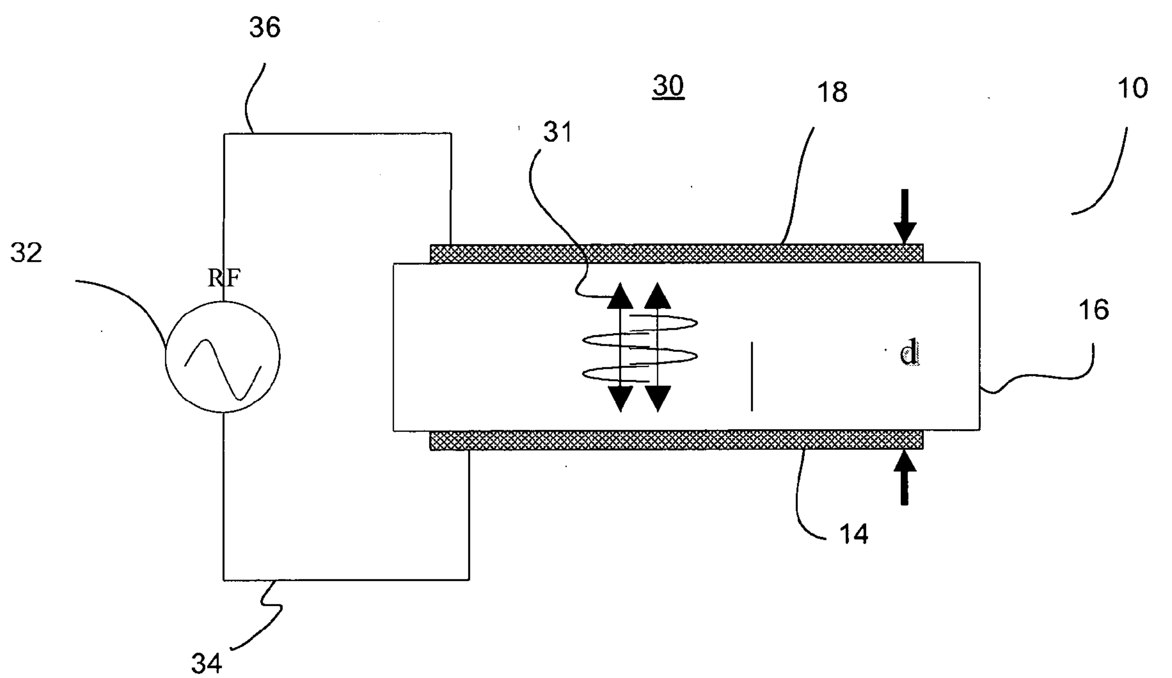
(57) **ABSTRACT**

An FBAR device may be chemically functionalized by depositing an interactive layer so that targeted chemicals are preferentially adsorbed. Such miniaturized chemical sensors may be combined with wireless network technology. For example, a chemical sensor may be integrated in a cell phone, PDA, a watch, or a car with wireless connection and GPS. Since such devices are widely populated, a national sensor network may be established. Consequently, a national toxicity map can be generated in real time. Detailed chemical information may be obtained, such as if a chemical is released by a source fixed on ground or by a moving object, or if is spread by explosives or by wind and so on.



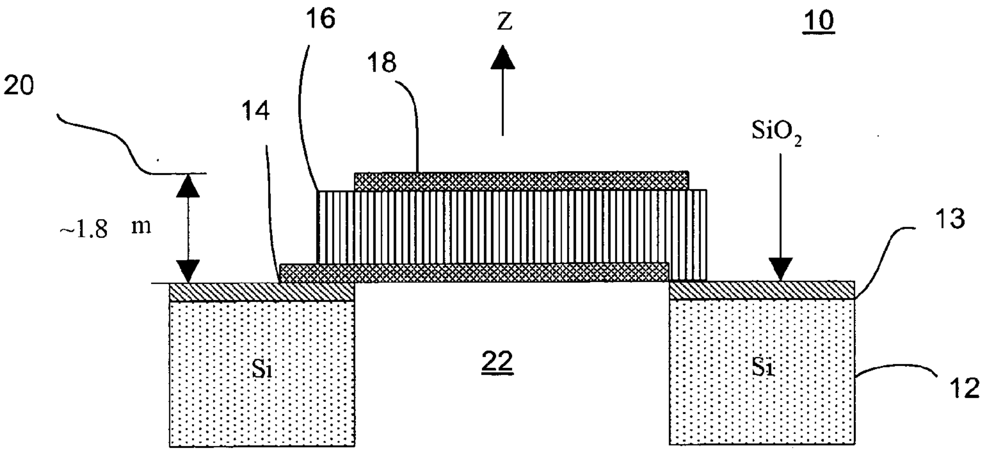


Fig. 1

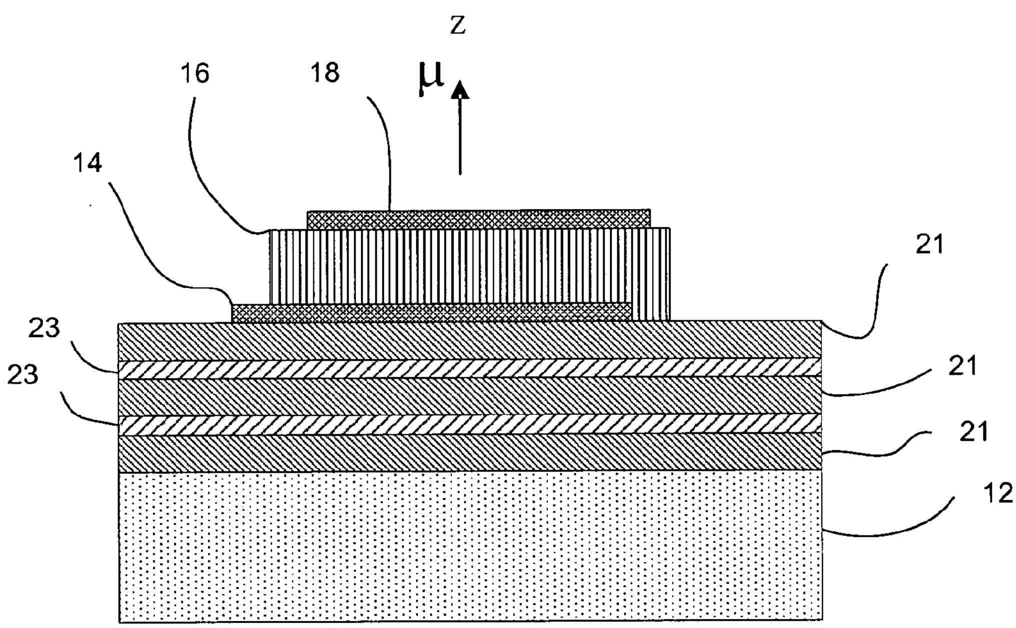


Fig. 2

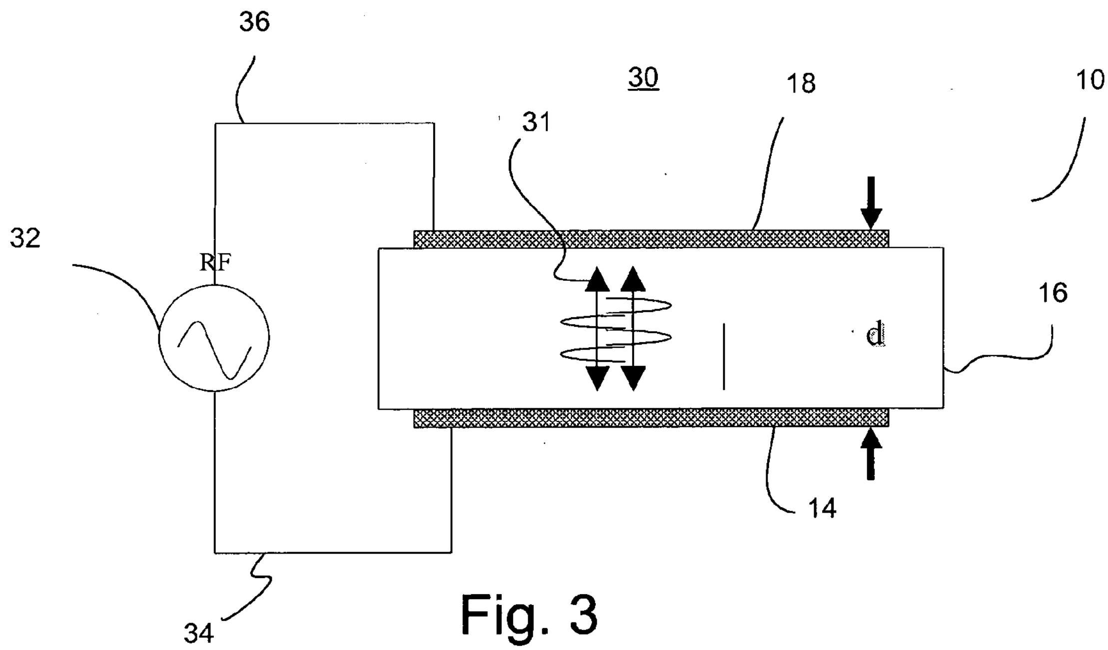


Fig. 3

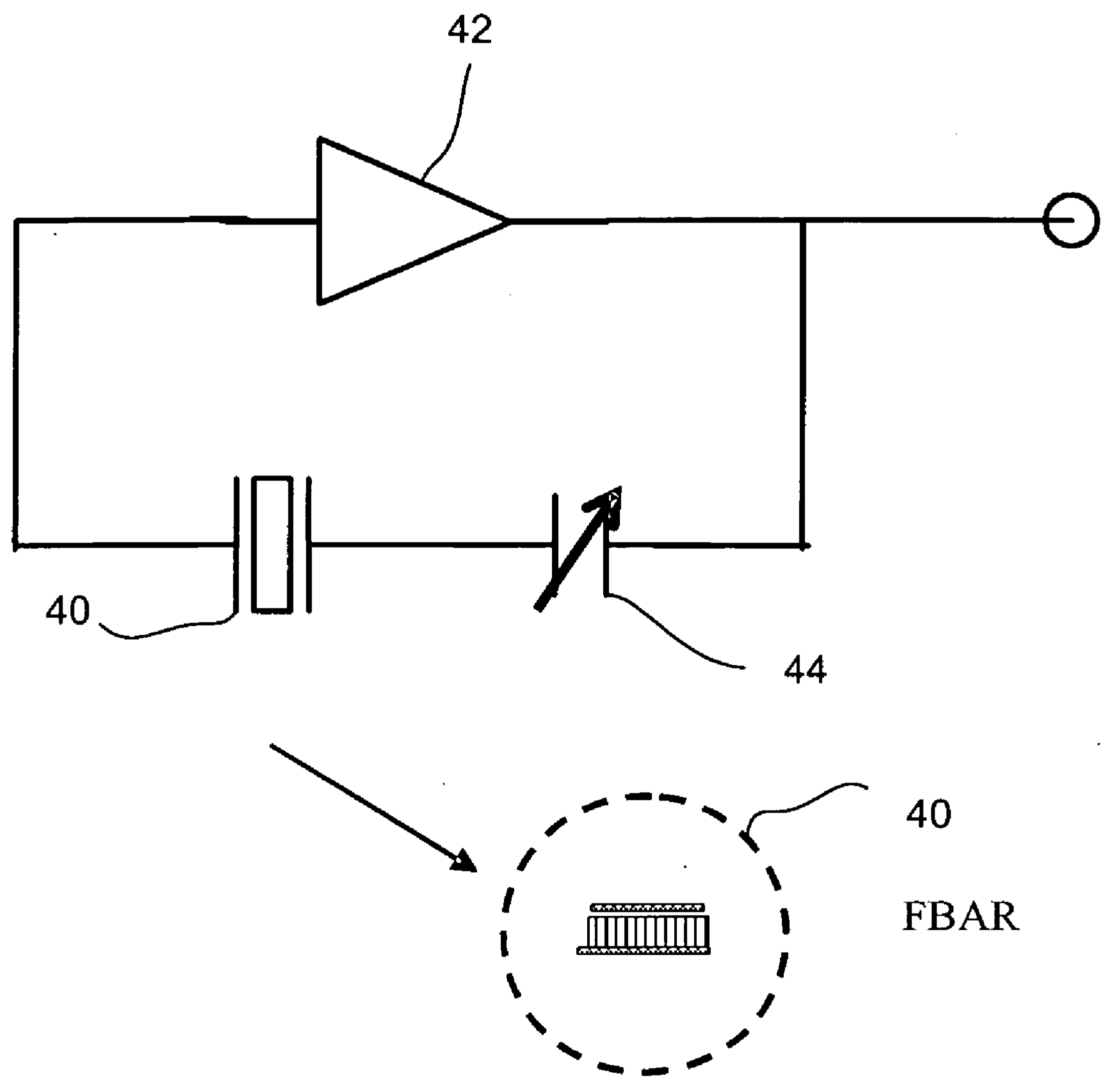


Fig. 4

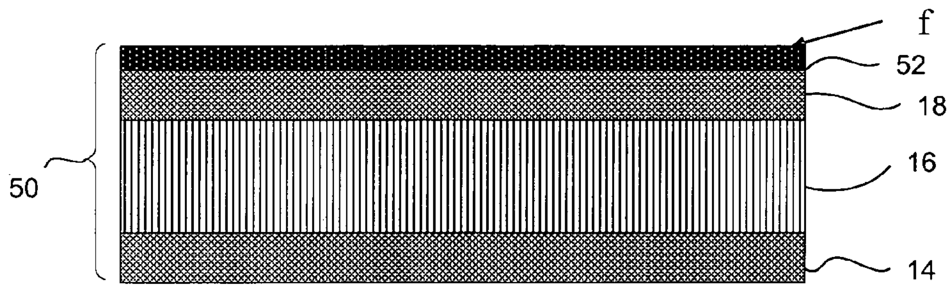


Fig. 5

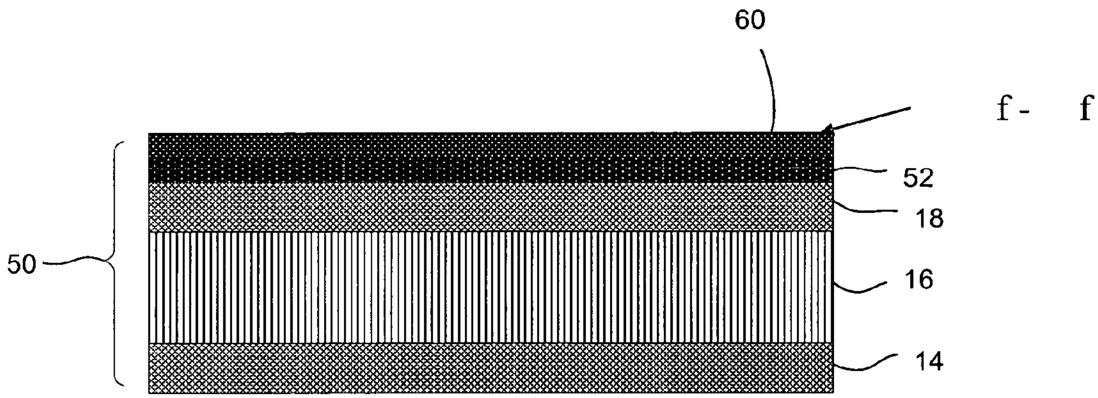


Fig. 6

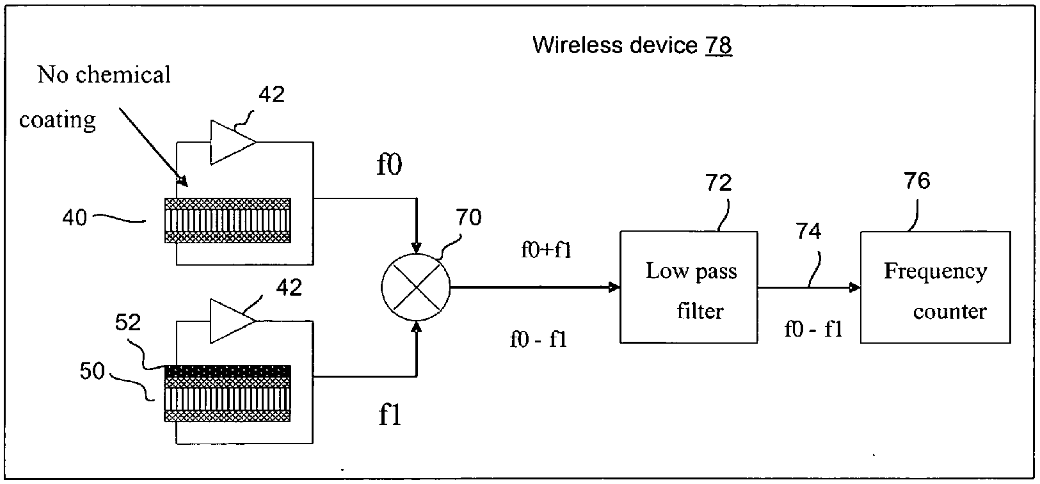

Wireless device 78
No chemical
coating
42
f0
72
76
40
70
74
f0+f1
Low pass
filter
Frequency
counter
42
52
50
f0 - f1
f0 - f1
f1

Fig. 7

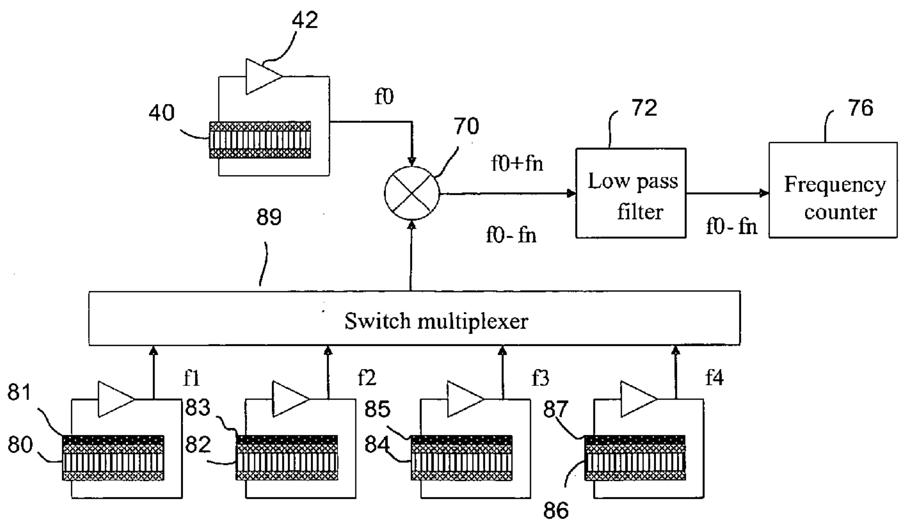

42
40
f0
70
72
76
f0+fn
Low pass
filter
Frequency
counter
89
f0- fn
f0- fn
Switch multiplexer
81
f1
f2
f3
f4
83
85
87
80
82
84
86

Fig. 8

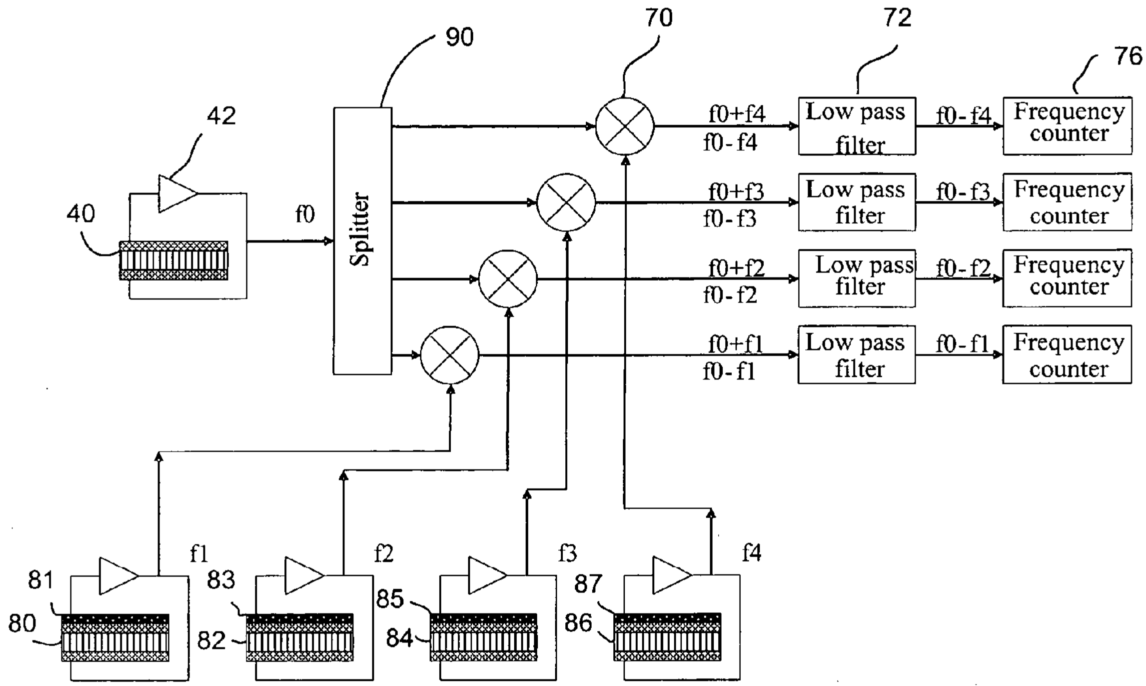

90
70
72
76
42
40
f0
Splitter
f0+f4
f0- f4
Low pass filter
f0- f4
Frequency counter
f0+f3
f0- f3
Low pass filter
f0- f3
Frequency counter
f0+f2
f0- f2
Low pass filter
f0- f2
Frequency counter
f0+f1
f0- f1
Low pass filter
f0- f1
Frequency counter
f1
f2
f3
f4
81
80
83
82
85
84
87
86

Fig. 9

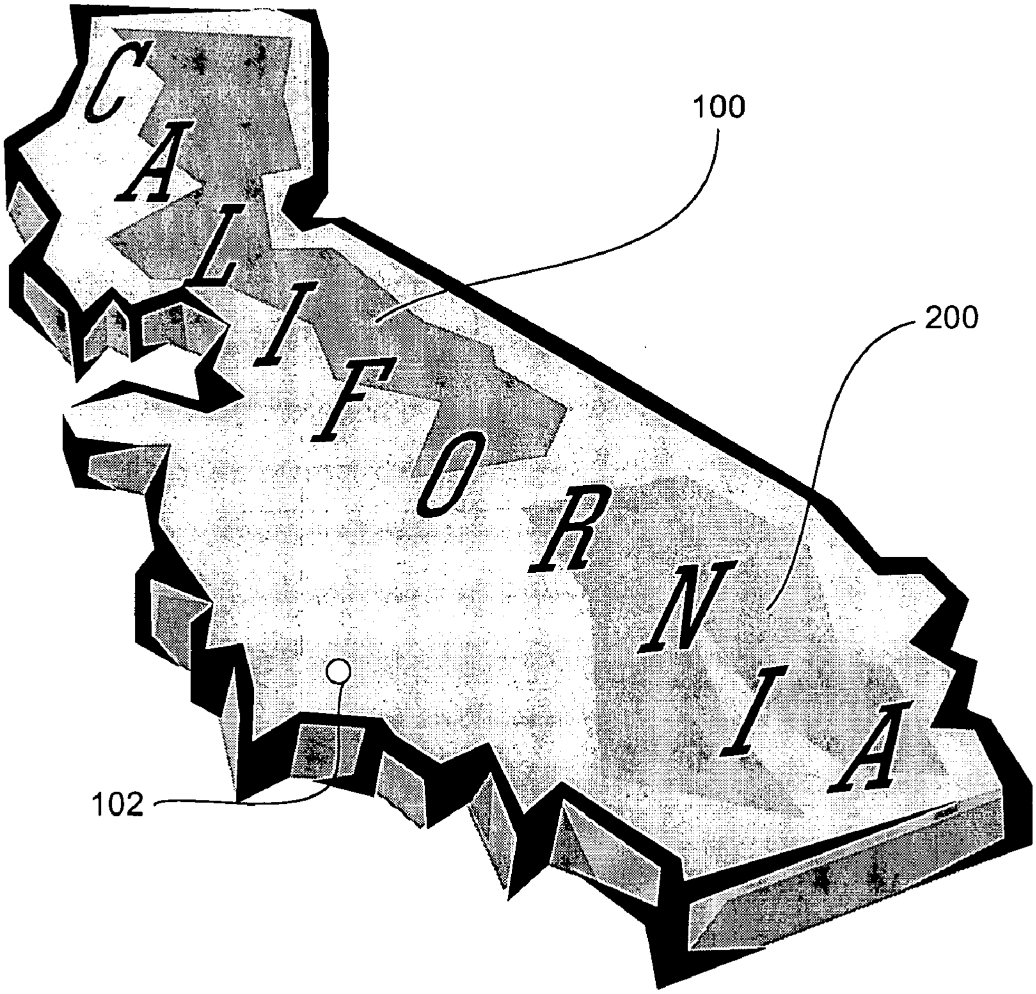


Fig. 10

GAS PHASE CHEMICAL SENSOR BASED ON FILM BULK RESONATORS (FBAR)

FIELD OF THE INVENTION

[0001] Embodiments of the present invention relate to film bulk acoustic resonators (FBARs) and, more particularly to such devices used as chemical sensors.

BACKGROUND INFORMATION

[0002] Film bulk acoustic resonator (FBAR) technology may be used as a basis for forming many of the frequency components in modern wireless systems. For example, FBAR technology may be used to form filter devices, oscillators, resonators, and a host of other frequency related components. FBAR may have advantages compared to other resonator technologies, such as Surface Acoustic Wave (SAW) and traditional crystal oscillator technologies. In particular, unlike crystals oscillators, FBAR devices may be integrated on a chip and typically have better power handling characteristics than SAW devices.

[0003] The descriptive name given to the technology, FBAR, may be useful to describe its general principals. In short, "Film" refers to a thin piezoelectric film such as Aluminum Nitride (AlN) sandwiched between two electrodes. Piezoelectric films have the property of mechanically vibrating in the presence of an electric field as well as producing an electric field if mechanically vibrated. "Bulk acoustic" refers to the acoustic wave generated within the bulk of the films stack. As opposed to the SAW device, the acoustic wave is on the surface of the piezoelectric substrate (or film).

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] FIG. **1** is a side view of a free-standing membrane film bulk acoustic resonator (FBAR);

[0005] FIG. **2** is a side view of a solidly mounted membrane film bulk acoustic resonator (FBAR);

[0006] FIG. **3** is a view illustrating the operation of an FBAR;

[0007] FIG. **4** is a simple oscillator circuit using an FBAR;

[0008] FIG. **5** is a cut-away side view of an FBAR coated with an interactive layer so that targeted chemicals are preferentially adsorbed;

[0009] FIG. **6** is a cut-away side view of the FBAR shown in FIG. **5** after a targeted chemical is present with the interactive layer;

[0010] FIG. **7** is a diagram showing an embodiment of the invention of readout electronics of using two FBARs to get the comparative signal. using FBARs as miniature chemical detectors for example;

[0011] FIG. **8** is a diagram showing yet another embodiment of the invention using FBARs as miniature chemical detectors;

[0012] FIG. **9** is a diagram showing yet another embodiment of the invention using FBARs as miniature chemical detectors; and

[0013] FIG. **10** is an example of a toxicity map for a geographic region according to an embodiment of the invention.

DETAILED DESCRIPTION

[0014] Numerous specific details may be set forth herein to provide a thorough understanding of the embodiments. It will be understood by those skilled in the art, however, that the embodiments may be practiced without these specific details. In other instances, well-known methods, procedures, components and circuits have not been described in detail so as not to obscure the embodiments. It can be appreciated that the specific structural and functional details disclosed herein may be representative and do not necessarily limit the scope of the embodiment.

[0015] A free-standing FBAR device **10** is schematically shown in FIG. **1**. The FBAR device **10** may be formed on the horizontal plane of a substrate **12**, such as silicon and may include an SiO_2 layer **13**. A first layer of metal **14** is placed on the substrate **12**, and then a piezoelectric layer **16** is placed onto the metal layer **14**. The piezoelectric layer **16** may be Zinc Oxide (ZnO), Aluminum Nitride (AlN), Lead Zirconate Titanate (PZT), or any other piezoelectric material. A second layer of metal **18** is placed over the piezoelectric layer **14**. The first metal layer **14** serves as a first electrode **14** and the second metal layer **18** serves as a second electrode **18**. The first electrode **14**, the piezoelectric layer **16**, and the second electrode **18** form a stack **20**. As shown, the stack may be, for example, around 1.8 μm thick. A portion of the substrate **12** behind or beneath the stack **20** may be removed using back side bulk silicon etching to form an opening **22**. The back side bulk silicon etching may be done using deep trench reactive ion etching or using a crystallographic-orientation-dependent etch, such as Potassium Hydroxide (KOH), Tetra-Methyl Ammonium Hydroxide (TMAH), and Ethylene-Diamene Pyrocatechol (EDP).

[0016] The resulting structure is a horizontally positioned piezoelectric layer **16** sandwiched between the first electrode **14** and the second electrode **16** positioned above the opening **22** in the substrate **12**. In short, the FBAR **10** comprises a membrane device suspended over an opening **22** in a horizontal substrate **12**.

[0017] FIG. **2** shows yet another embodiment FBAR device comprising a solidly mounted membrane FBAR. In this case, the substrate **12** comprises a multilayer periodic structure, such as alternating layers of SiO_2 **21** and Tungsten (W) **23**. Similar to above, a first layer of metal **14** is placed on the upper SiO_2 layer **21**, and then a piezoelectric layer **16** is placed onto the metal layer **14**. The piezoelectric layer **16** may be Zinc Oxide (ZnO), Aluminum Nitride (AlN), Lead Zirconate Titanate (PZT), or any other piezoelectric material. A second layer of metal **18** is placed over the piezoelectric layer **14**. Again, the first metal layer **14** serves as a first electrode **14** and the second metal layer **18** serves as a second electrode **18**. The alternating layers, **21** and **23**, of the periodic structure reflects acoustic waves in the Z direction so that the acoustic wave is efficiently trapped in the solidly mounted membrane at the FBAR resonant frequency.

[0018] FIG. **3** illustrates the schematic of an electrical circuit **30** which includes a film bulk acoustic resonator **10**. The electrical circuit **30** includes a source of radio frequency "RF" voltage **32**. The source of RF voltage **32** is attached to the first electrode **14** via electrical path **34** and attached to the second electrode **18** by the second electrical path **36**. The entire stack can freely resonate in the Z direction **31** when an RF voltage **32** at resonant frequency is applied. The resonant frequency is determined by the thickness of the membrane or the thickness of the piezoelectric layer **16** which is designated by the letter "d" or dimension "d" in FIG. **3**. The resonant frequency is determined by the following formula:

$f_0 \approx V/2d$, where

[0019] f_0=the resonant frequency,

[0020] V=acoustic velocity of piezoelectric layer, and

[0021] d=the thickness of the piezoelectric layer.

[0022] It should be noted that the structure described in FIGS. **1-3** can be used either as a resonator or as a filter. To form an FBAR, piezoelectric films **16**, such as ZnO, PZT and AlN, may be used as the active materials. The material properties of these films, such as the longitudinal piezoelectric coefficient and acoustic loss coefficient, are parameters for the resonator's performance. Performance factors include Q-factors, insertion loss, and the electrical/mechanical coupling. To manufacture an FBAR the piezoelectric film **16** may be deposited on a metal electrode **14** using for example reactive sputtering. The resulting films are polycrystalline with a c-axis texture orientation. In other words, the c-axis is perpendicular to the substrate.

[0023] FIG. **4** is a simple circuit illustrating how an FBAR **40** may be used as a phase control element in a feedback loop of an oscillator circuit. As shown, the circuit comprises an amplifier **42** and a feedback loop including an FBAR **40** and an optional element such as a varactor **44**.

[0024] Oscillation involves two conditions at the oscillation frequency. First, the closed loop phase shift should be 2 np, where p is the phase and n is an integer. The loop gain should be greater than or equal to unity. The stability of the oscillator is determined by that of the loop phase delay. Further, the frequency characteristics of the FBAR **40** tend to be influenced by temperature which may be undesirable for wireless communication applications. For example, for cell phone applications, the operation temperature specification may be between −35 and +85° C. Such extreme temperature variations may be encountered for example in a closed automobile where a cell phone may be kept. Because of temperature induced frequency drift, pass band windows are typically designed appreciably larger than they otherwise would be and transition bands sharper. Such design constraints tend to degrade insertion loss and demand more stringent processing requirements leading to reduced production yield.

[0025] According to embodiments of the invention, the surface of the FBAR **40** may be chemically functionalized by depositing an interactive layer so that targeted chemicals are preferentially adsorbed. When a chemical specie is adsorbed, the resonance frequency decreases due to mass loading effect. Sensitivity of FBAR with respect to absorbed chemicals may be very high. Miniaturized chemical sensors such as those described may be combined with wireless network technology. For example, a chemical sensor may be integrated in a cell phone, PDA, a watch, or a car with wireless connection and GPS. Since such devices are widely populated, a national sensor network may be established. Consequently, a national toxicity map can be generated in real time. Detailed chemical information may be obtained, such as if a chemical is released by a source fixed on ground or by a moving object, or if is spread by explosives or by wind and so on.

[0026] FIG. **5** shows a cut-away side view of the FBAR stack previously described comprising the lower electrode **14** and upper electrode **18** sandwiching the piezoelectric layer **14**. Atop the upper electrode **18** an interactive layer **50** is placed. The interactive layer **50** is selected such that targeted chemicals are preferentially absorbed or collected. Once assembled, the FBAR will have a resonant frequency (f).

[0027] FIG. **6** shows the same stack as in FIG. **5** including electrodes **14** and **18**, and piezoelectric layer **16** with a targeted chemical **60** absorbed or collected from the atmosphere associated with the interactive layer **50**. This will tend to decrease the resonant frequency of the FBAR by Δf.

[0028] Different materials may comprise the interactive layer to target specific chemicals desired to be detected in the atmosphere. In general, the synthesis or selection of a perfectly selective coating for each analyte of interest (target chemical vapor) may be difficult, particularly if large numbers of chemicals are involved. Thus, each detector may have a different sensitive coated films. In combination with cluster analysis-based pattern recognition of the responses, a unique signature for each of mixed gases may be recognized. This is demonstrated for example in M. K. Bailer et al., A Cantilever Array-Based Artificial Nose, *Ultrmicroscopy* 82 (2000) 1-9.

[0029] As previously noted, when temperature changes, the resonance frequency of a FBAR changes correspondingly. This temperature drift should be taken account of in order to have accurate chemical detection.

[0030] As shown in FIG. **7**, two identical FBAR resonators, **40** and **50**, may be placed side by side, but only one of the resonators **50** includes the chemically interactive layer **52** leaving the other resonator **40** as a reference, so the differential frequency change gives the chemical detection signal. This differential measurement technique may also be effective in improving yield. This is because there may be resonance frequency variations of FBAR across the wafer during manufacture and from wafer to wafer due to film thickness variations. By measuring differential frequency change, these processing variations may be canceled out. The outputs, f**0** and f**1**, of the resonators **40** and **50** are combined at combiner **70** and passed through a low pass filter **72** to produce a differential output signal **74**. A frequency counter **76** counts the differential frequency signal **74**. A change in frequency may be used to determine that a targeted chemical is present and has been absorbed by the interactive layer **52**.

[0031] The circuit shown in FIG. **7** may be part of a wireless device **78** such as a cell phone, PDA, or the like. With such wireless devices widely distributed by consumers over a large geographic region data collected from many such devices may be used to monitor chemicals in the air. Consequently, a national or regional toxicity map may be generated in real time. Detailed chemical information can be obtained, such as if a chemical is released by a source fixed on ground or by a moving object, or if is spread by explosives or by wind and so on.

[0032] FIG. **8** illustrates yet another embodiment of the present invention. Similar to FIG. **7**, but comprising an FBAR detector array. Multiple FBARs **40**, **80**, **82**, **84**, and **86** may be integrated on the same silicon, each of the FBAR resonators **80**, **82**, **84**, and **86** may be coated with a different chemical detection layer **81**, **83**, **85**, and **87**, for detecting different chemical species. The remaining FBAR resonator **40** may be left uncoated to again act as a reference. A specie might cause several resonators to shift frequency, the relative frequency shift magnitude can provide a unique signature of the specie. A switching multiplexer **89** may be used to gather signal information from each resonator sequentially. Again, these signals are combined at combiner **70**, passed through a low-pass filter **72** and the resultant differential signal (f**0**-fn) counted at frequency counter **76** to detect changes. For specific applications, the multiplexer may be programmed to collect data from selected subset of FBARs **80**, **82**, **84**, and **86**.

[0033] FIG. **9** shows yet another embodiment of the present invention similar to that shown in FIG. **8**. The difference being that the signals f**1**-f**4** from the coated FBAR resonators **80**, **82**, **84**, and **86** are not multiplexed but separately combined at combiners **70** with the reference signal f**0** from the uncoated FBAR resonator **40** which is split by signal splitter **90**. Again, each of the combined signals are passed through separate low-pass filters **72** and the resultant differential signal counted by dedicated frequency counters **76** to detect changes indicating the presence of targeted chemicals.

[0034] Alternatively, surface-acoustic-wave (SAW) or cantilever type resonators may be used for miniaturized chemical detectors. However, the sensitivity of SAW is limited by the fact that its frequency shift with mass loading is a secondary effect; the cantilever resonator (and its derivative such as a mechanical resonating membrane) suffers from air damping effect and therefore low Q and low sensitivity. The FBAR resonators described herein are very sensitive to air damping effect but insensitive to air damping. Further, FBAR has much smaller insertion loss (IL) than SAW. Also, FBAR is fabricated on silicon, therefore can be easily integrated with other silicon devices.

[0035] As illustrated in FIG. **10**, for example, if a chemical sensor is integrated in a cell phone (PDA), or a watch, or a car with wireless connection and GPS, and such devices are widely populated, then a sensor network may be established. Consequently, a national toxicity map can be generated in real time. FIG. **10** illustrates what a toxicity map may look like for the state of California. For examples wireless consumer devices used by people in various geographic regions may report chemical detection to a central facility **102** to map the spread of various air born chemicals **100** and **200**. Detailed chemical information may be obtained, such as if a chemical is released by a source fixed on ground or by a moving object, or if is spread by explosives or by wind and so on.

[0036] The above description of illustrated embodiments of the invention, including what is described in the Abstract, is not intended to be exhaustive or to limit the embodiments to the precise forms disclosed. While specific embodiments of, and examples for, the invention are described herein for illustrative purposes, various equivalent modifications are possible, as those skilled in the relevant art will recognize. These modifications can be made to embodiments of the invention in light of the above detailed description.

[0037] The terms used in the following claims should not be construed to limit the invention to the specific embodiments disclosed in the specification. Rather, the following claims are to be construed in accordance with established doctrines of claim interpretation.

What is claimed is:

1. An apparatus, comprising:

a first frequency bulk film acoustic resonator (FBAR) device;

a second FBAR device coated with a target chemical selective layer; and

means for determining a differential frequency output of the first FBAR device and the second FBAR device to determine the presence of the target chemical.

2. The apparatus as recited in claim 1 wherein the first FBAR device and the second FBAR device each comprise:

an amplifier; and

a feedback loop having an FBAR connected between the amplifier output and amplifier input.

3. The apparatus as recited in claim 1 further comprising:

a wireless device for transmitting data indicating the presence of the target chemical to a remote location to generate a toxicity map for a region.

4. The apparatus as recited in claim 1 further comprising:

a plurality of the second FBAR devices coated each coated with a target chemical selective layer to detect a different chemical.

5. The apparatus as recited in claim 1, wherein the means for means for determining a differential frequency output of the first FBAR device and the second FBAR device comprises:

a combiner to receive an output signal from the first FBAR device and the second FBAR device to output a combined signal;

a low-pass filter to receive the combined signal and output a differential output signal; and

a frequency counter to determine the differential frequency.

6. The apparatus as recited in claim 1, wherein the means for means for determining a differential frequency output of the first FBAR device and the second FBAR device comprises:

a multiplexer to multiplex signals from a plurality of the second FBAR devices;

a combiner to receive an output signal from the first FBAR device and the multiplexer to output a combined signal;

a low-pass filter to receive the combined signal and output a differential output signal; and

a frequency counter to determine the differential frequency.

7. The apparatus as recited in claim 1, wherein the means for means for determining a differential frequency output of the first FBAR device and the second FBAR device comprises:

a splitter for splitting the output the first FBAR device;

a plurality of combiners each to receive a signal from the splitter and a signal from each of a plurality of the second FBAR devices, each combiner to output a combined signal;

a plurality of low-pass filters each connected to one of the combiners; and

a plurality of frequency counters each to determine a differential frequency.

8. A method, comprising:

coating a frequency bulk film acoustic resonator (FBAR) in an FBAR oscillator with a target chemical selective layer;

determining a differential frequency between the coated FBAR oscillator and a reference uncoated FBAR oscillator; and

determining the presence of the target chemical from the differential frequency.

9. The method as recited in claim 8 further comprising:

using a wireless device to transmit information indicating the presence of the target chemical to a remote location.

10. The method as recited in claim 9, further comprising:

placing a plurality wireless devices in consumer products distributed over a geographic region.

11. The method as recited in claim 10 further comprising:

gathering at the remote location information from the plurality of wireless devices; and

producing a toxicity map for the geographic region.

12. The method as recited in claim 8 further comprising:

coating a frequency bulk film acoustic resonator (FBAR) in a plurality of FBAR oscillators with a target chemical selective layer to target different chemicals.

13. The method as recited in claim comprising:

programming a multiplexer to select ones of plurality of FBAR oscillators.

14. A system, comprising:

a plurality of wireless devices each comprising a frequency bulk film acoustic resonator (FBAR) coated with a target chemical selective layer;

a remote receiver location for receiving information from the plurality of wireless devices indicating the presence of a target chemical in locations of the plurality of wireless devices.

15. The system as recited in claim 14, wherein the information is used to generate a toxicity map.

16. The system as recited in claim 14 wherein the plurality of wireless devices comprise positioning systems.

17. The system as recited in claim 16, wherein the plurality of wireless devices comprise cell phones.

18. The system as recited in claim 16 wherein the plurality of wireless devices comprise personal digital assistants.

19. The system as recited in claim 14 wherein ones of the plurality of wireless devices comprise arrays of FBAR devices each comprising a different target chemical selective layer.

* * * * *