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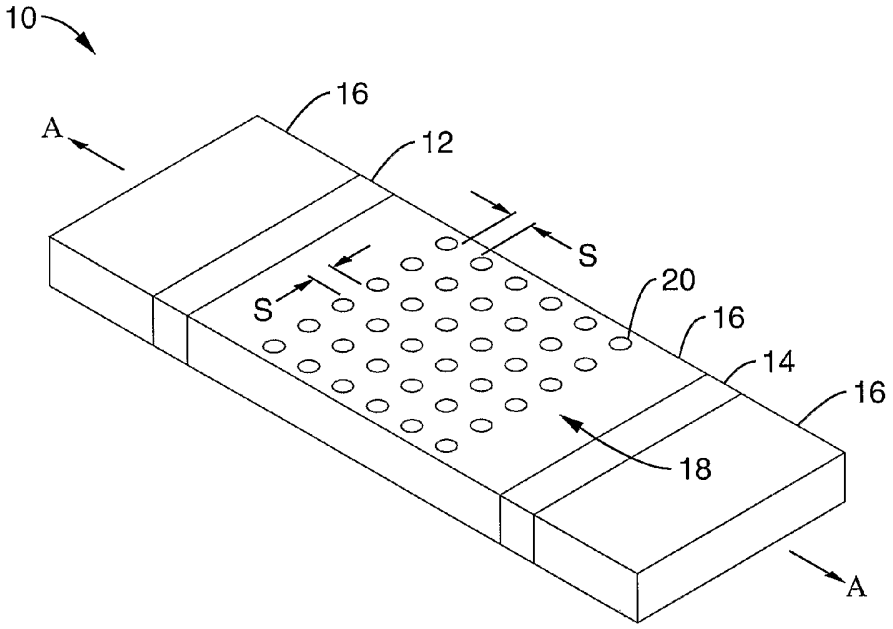
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(54) Title: MICROELECTROMECHANICAL BANDPASS FILTERS FOR RADIO FREQUENCY SIGNAL PROCESSING



(57) Abstract: A set of extensional-mode microelectromechanical (MEMS) filters has been designed to achieve high resonant frequency, and high quality factors for radio frequency applications. The filter designs allow for easy coupling of individual resonators to form narrow band-pass filters for signal processing, and robust fabrication. The filter designs also eliminate energy dissipation into anchoring points and may be used for the general purpose of enhancing Q-factor in any extensional micro-mechanical devices.

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MICROELECTROMECHANICAL BANDPASS FILTERS FOR RADIO FREQUENCY SIGNAL PROCESSING

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority from U.S. provisional application serial number 60/615,323 filed on October 1, 2004, incorporated herein by reference in its entirety.

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Not Applicable

INCORPORATION-BY-REFERENCE OF MATERIAL SUBMITTED ON A COMPACT DISC

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BACKGROUND OF THE INVENTION

1. Field of the Invention

[0004] This invention pertains generally to microfabricated signal processors, and more particularly to micro signal processors which include microelectromechanical components.

2. Description of Related Art

[0005] A filter processes a signal applied to its input such that the signal at the output has desirable properties according to the specifications for a particular application. High frequency, high frequency-selectivity, band-pass filters have been needed and used in telecommunications systems, such as radio-frequency (RF) receivers, mobile/cellular phone networks, and satellite communication systems. As the telecommunication industry began expanding rapidly and numerous other applications started proliferating, the cost, size, and performance requirements have driven the design of filters to other technologies such active RC filters, switched-capacitor filters, charge-transfer devices filters, digital filters, and mechanical filters.

[0006] Mechanical filters, which specifically refer to mechanically coupled acoustic resonators, excel in their radical reduction in size and power consumption. Owing to the fact that the speed of acoustic waves is around four orders of magnitude less than electromagnetic waves, mechanical resonators are usually four orders of magnitude smaller than their electronic counter parts such as active RC filters. Furthermore, because of very low loss of mechanical resonators, the quality factor (Q factor) of mechanical resonators is extremely high (e.g., up to 10,000).

[0007] An alternative method which also employs acoustic waves for signal processing is related to surface acoustic waves (SAW), and devices which use this method are called SAW devices. Since 1960, the development of SAW devices has overcome its disadvantages of large insertion loss and low power durability. Vibrating SAW and crystal resonators are widely used in current wireless communication sub-systems for frequency selection and reference due to their high quality factor (Q factor) and extraordinary temperature stability. However, being off-chip components, these mechanical devices must interface with integrated electronics at board level, and this constitute a severe bottleneck to miniaturization and performance of heterodyning transceivers.

[0008] In recent years, micromechanical resonators with similar performance

of their macro, thus low frequency counterparts, have been demonstrated using IC-compatible, poly-silicon surface-micromachining technology. With Q's about 10,000 under vacuum and center frequency temperature coefficients in the range of -10ppm/°C, polysilicon micro resonators can serve well as miniaturized substitute for crystals in a variety of high-Q oscillator and filtering applications. To date, high-Q micro-resonators made of folded beam, flexural beam and dilation disk configurations have been demonstrated in the frequency range from several hundreds kilohertz to 150 megahertz.

[0009] However, to raise the central frequencies of resonators is not simply to shrink the size of existing devices, and numbers of challenges are being faced. For example, previous designs all focused on a bottom up method (i.e., trying to build up a filter by coupling more and more resonators). To date, no one has tried to design a signal processing device from a systematic point of view. Additionally, as frequency increases, the size of microresonators, which is approximately equal to the speed of relevant acoustic wave divided by frequency, decreases accordingly and becomes stricter on design. Furthermore, it has been shown that there is a trend that Q-factor of resonators dwindles with the shrinking resonator sizes. This is because the energy dissipation into substrates through its anchors is becoming more and more severe as compared to the acoustic energy stored in the resonators.

[0010] Accordingly, an object of the present invention is to provide a high-pass micro-mechanical filter design from a top-down perspective of view. The novel systematic design of the present invention allows robust fabrication of filters with frequency up to GHz range. This provides a general solution to eliminating acoustic energy loss in microresonators to the substrate to enhance Q factors.

BRIEF SUMMARY OF THE INVENTION

[0011] The present invention comprises a set of extensional-mode microelectromechanical (MEMS) devices for achieving high-pass, low pass, and narrow band-pass filter functions, and for achieving mechanical resonators with high resonant frequency and high quality factors for radio

frequency applications. This invention allows for easy coupling of individual resonators to form narrow band-pass filters for signal processing, and robust fabrication. The inventive filters devices eliminate energy dissipation into anchoring points and may be used for general purpose of enhancing Q-factor in any extensional micro-mechanical devices.

[0012] The design principle of the present invention can best be understood qualitatively by considering conductive wire meshes for electromagnetic wave screening. Metallic wire meshes are commonly used as radiation polarizers and filters, and there have been several studies of the electrodynamics of such systems. In those studies, it has been shown that transmittance through a wire mesh is attenuated when the wavelength of the incident electromagnetic waves becomes larger than the mesh size. This "high-pass" effect comes from the fact that conductive wires are not penetrable to electromagnetic waves to a depth more than the skin-depth. Therefore, for wavelengths larger than the mesh size, the electromagnetic waves are transmitted through tunneling or the surface states, and the transmittance through the wire mesh is significantly attenuated.

[0013] According to an aspect of the invention, a filter apparatus comprises a membrane comprising a first material and having a plurality of spaced-apart periodic variations forming an array wherein acoustic waves incident on the membrane having a wavelength greater than the spacing between the periodic variations are attenuated and wherein acoustic waves incident on the membrane have a wavelength less than the spacing between the periodic variations pass through the membrane. In one embodiment, the periodic variations comprise holes. In one embodiment, the holes are filled with a second material having properties different than the first material. In one embodiment, the periodic variations comprise a second material in the membrane that has different properties than the first material. In one mode, for wavelengths greater than the spacing between the periodic variations in the array, the incident waves can only tunnel through the array by surface states. In one embodiment, the filter further comprises an input transducer coupled to the membrane, and an output transducer coupled to the

membrane, wherein the input transducer is configured to convert electrical signals into acoustic waves along the membrane, and wherein the output transducer is configured to convert acoustic waves which have passed through the membrane to electrical signals. In one mode, increasing the number of periodic variations in the array produces sharper, step-function-like, filter characteristics. In one embodiment, the filter further comprises an acoustic resonator surrounded by the array of periodic variations wherein acoustic waves having a resonance frequency within a range of resonant frequencies of the resonator are confined by the resonator.

[0014] According to another aspect of the invention, a filter apparatus comprises a membrane having a plurality of spaced-apart holes forming an array wherein acoustic waves incident on the membrane having a wavelength greater than the spacing between said holes are attenuated and wherein acoustic waves incident on the membrane having a wavelength less than the spacing between said holes pass through the membrane. In one embodiment, the membrane comprises a first material and the holes are filled with a second material having properties different than the first material. In one mode, for wavelengths greater than the spacing between the holes in said array, the incident waves can only tunnel through the array by surface states. In one embodiment, the filter further comprises an input transducer coupled to the membrane and an output transducer coupled to the membrane wherein the input transducer is configured to convert electrical signals into acoustic waves along the membrane and wherein the output transducer is configured to convert acoustic waves which have passed through the membrane to electrical signals. In one mode, increasing the number of holes in the array produces sharper, step-function-like, filter characteristics. In one embodiment, the filter further comprises an acoustic resonator surrounded by the array of holes wherein acoustic waves having a resonance frequency within a range of resonant frequencies of the resonator are confined by the resonator.

[0015] According to a still further aspect of the invention, a filter apparatus comprises a membrane having a plurality of spaced-apart holes forming an

array and an acoustic resonator surrounded by the array of holes wherein acoustic waves having a resonance frequency within a range of resonant frequencies of the resonator are confined by the resonator, wherein acoustic waves incident on the membrane having a wavelength greater than the spacing between the holes are attenuated, and wherein acoustic waves incident on the membrane having a wavelength less than the spacing between the holes pass through the membrane. In one embodiment, the membrane comprises a first material and the holes are filled with a second material having properties different than the first material. In one mode, for wavelengths greater than the spacing between the holes in the array, the incident waves can only tunnel through the array by surface states. In one embodiment, the filter further comprises an input transducer coupled to the membrane and an output transducer coupled to the membrane wherein the input transducer is configured to convert electrical signals into acoustic waves along the membrane and wherein the output transducer is configured to convert acoustic waves which have passed through the membrane to electrical signals. In one mode, increasing the number of holes in the array produces sharper, step-function-like, filter characteristics.

[0016] Further aspects of the invention will be brought out in the following portions of the specification, wherein the detailed description is for the purpose of fully disclosing preferred embodiments of the invention without placing limitations thereon.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING(S)

[0017] The invention will be more fully understood by reference to the following drawings which are for illustrative purposes only:

[0018] FIG. 1 schematically illustrates an embodiment of a high pass filter according to the invention.

[0019] FIG. 2 is a graph illustrating the spectrum response of a high pass filter of the type shown in FIG. 1.

[0020] FIG. 3 is a series of graphs illustrating the operational characteristics of a high pass filter of the type shown in FIG. 1.

[0021] FIG. 4A schematically illustrates an embodiment of a one-dimensional extensional resonator according to the invention.

[0022] FIG. 4B is a graph showing acoustic reflectivity characteristics of an acoustic mirror employed in the resonator shown in FIG. 4A.

[0023] FIG. 5 schematically illustrates an embodiment of a two-dimensional extensional resonator according to the invention.

[0024] FIG. 6 schematically illustrates an embodiment of a microelectromechanical high pass filter for radio signal processing according to the invention.

[0025] FIG. 7 schematically illustrates an embodiment of an extensional resonator beam suspended between two acoustic mirrors according to the invention.

[0026] FIG. 8 schematically illustrates two coupled extensional resonator beams suspended between two acoustic mirrors according to the invention.

DETAILED DESCRIPTION OF THE INVENTION

[0027] By way of example, and not of limitation, one embodiment of a high-pass, radio frequency, micromechanical filter according to the present invention generally comprises (a) a first transducer which converts electromagnetic waves to mechanical acoustic waves, (b) a high-pass acoustic filter comprising a membrane with hole arrays, and (c) a second transducer which converts mechanical acoustic waves to electromagnetic waves.

[0028] FIG. 1 schematically illustrates a high-pass filter 10 according to an embodiment of the invention. Note that the filter is designed to operate in a vacuum. The exemplary embodiment comprises two transducers 12, 14 with an intermediate filter membrane 16 having periodical 6x6 hole arrays 18. The left transducer 12 converts electrical signals into acoustic waves along the membrane 16, and the right transducer 14 converts acoustic waves which have passed through the hole arrays 18 back to electric signals. In use, the entire structure typically would be supported by anchors *A* and placed in a housing that is evacuated. While the high-pass filtering functionality depends on the periodicity of the hole arrays and the acoustic properties (Young's

modulus and density) of the membrane material, the membrane can provide this high-pass functionality with any solid materials.

[0029] For filter design, preferably there should be a highest frequency of interest; for example, f_{max} high. The membrane thickness (h) should be much smaller (for example, 4 times smaller) than the wavelength of longitudinal acoustic waves in the bulk materials at f_{max}, or $h < 4V_L / f_{\max}$. Here V_L is the velocity of the longitudinal acoustic wave and can be calculated with the formula: $V_L = \sqrt{C_{11} / \rho}$, with C_{11} being a material stiffness coefficient, and ρ being density of the membrane material. At this small film thickness, there is only one symmetrical longitudinal wave that can propagate. The wavelength of such an acoustic wave can be calculated by using the dispersion relationship: $\lambda = \frac{V_T^2}{f}\sqrt{\frac{1}{V_T^2} - \frac{1}{V_L^2}}$ (e.g., see Ryer, Daniel and Dieulesaint, Eugene "Elastic Waves in Solids", Chapter 5.5, Springer 1996, incorporated herein by reference). Here V_T is the transverse acoustic wave velocity in bulk materials, $V_L = \sqrt{C_{66} / \rho}$ with C_{66} being another material stiffness coefficient. The cut-off frequency is located where the acoustic wavelength equals the period of the hole arrays (d): or $f = \frac{V_T^2}{d}\sqrt{\frac{1}{V_T^2} - \frac{1}{V_L^2}}$.

[0030] For better energy conversion or high electromechanical coupling, active piezo-materials such as zinc-oxide (ZnO), aluminum nitride (AlN), lead zirconate titanate (PZT), etc., can be used for the membranes, so that the electrical energy can be directly converted to acoustic energy by transducer 12, and acoustic energy after filtering can be converted back to electrical energy by transducer 14.

[0031] The membranes, for example, can either be made of pure piezomaterials, or multilayers of dielectric, piezo, and dielectric materials. The preferred practice is to have symmetrical materials layers in respect to the piezomaterial layers, so as to eliminate the excitation of flexural vibrations. For example, the membrane can be constructed by according to the following

process: (1) patterning of the bottom electrodes for transducers 12 and 14 using, for example, microphotolithography and lift-off processes (a common practice in microfabrication) on a silicon-on-insulator (SOI) wafer; (2) deposition of a dielectric layer of SiO_2; (3) deposition of a piezoelectric layer of ZnO; (4) deposition of another layer of dielectric layer of SiO_2; (5) patterning of top electrodes for transducers 12 and 14 as in step (1); (6) patterning and etching to form the final structures of the membrane including the hole arrays, and membrane widths etc.; and (7) releasing and suspending the membrane by etching the sacrificial layer Si (the top layer of the substrate).

[0032] Note that the cut-off frequency depends on the film thicknesses. For example, when the piezoelectrical ZnO layer is much thicker than the SiO_2 layers, then the cut-off frequency will mainly determined by the acoustic properties of the piezoelectric layer. On the other hand, when the SiO_2 layers are much thicker than the piezoelectrical ZnO layer, then the cut-off frequency will mainly determined by the acoustic properties of the SiO_2 layers.

[0033] It will be appreciated that acoustic waves cannot be transmitted through a vacuum. In other words, when the membrane is placed in a vacuum, the holes 20 shown in FIG. 1 function in a similar manner as metallic wires, and are not penetrable to the incident waves. Accordingly, the acoustic waves are restricted to passing through the spaces between the holes. However, for wavelengths larger than the spacing *S* between holes, the incident waves can only tunnel through the hole array by surface states. Therefore, transmission of low frequency (or high wavelength) incident waves having wavelengths greater than the spacing between the holes will be significantly attenuated. On the other hand, transmission of wavelengths less than the spacing between the holes will essentially be unaffected and those incident waves will pass through the membrane. Hence, the configuration functions as a high-pass filter.

[0034] Note that the shape of the transmission curve depends strongly on the number of lines of hole arrays. As more and more lines of hole arrays are stacked together, a sharper, step-function-like, high-pass filter will be obtained. Referring to FIG. 2, which depicts the spectrum response for filter

characteristics of n_1 and n_2 lines of holes ($n_2>n_1$), it can be seen that the filter becomes more step-function like when the number of lines of holes is increased. Here, *n* refers to the number of columns, where a column of holes is the line of holes parallel to the electrodes in FIG. 1.

[0035] The working principle of the high-pass filter for signal processing can be seen from FIG. 3. The spectral part of frequency lower than cut-off frequency of the high-pass filter is diminished, while the part of frequency higher than the cut-off frequency is transmitted without distortion. It will be appreciated that low-pass and bandpass filters function on similar principles.

[0036] Referring now to FIG. 4, our method for eliminating energy loss or enhancing the Q factor of micro-mechanical resonators is illustrated. FIG. 4(a) illustrates a structure 100 comprising an extensional resonator 102 which is supported between two acoustic mirrors 104, 106. Each of the acoustic mirrors 104, 106 comprise materials or structures 108, 110 with alternating varying acoustic impedances Z_1, Z_2 as shown. FIG. 4(b) illustrates the acoustic reflectivity of an acoustic mirror comprising 1D periodic structures of 5.08 μm width of Al and 4.6 μm width of W.

[0037] The thickness of each layer of the acoustic mirrors (or the individual layer thickness) should be a quarter of the acoustic wavelength in that material ($\lambda/4$), and the length of the resonator should be half of the acoustic wavelength of the resonator materials ($\lambda/2$). The wavelength of the acoustic waves at the desired frequency (*f*) can be calculated using the formula:

$\lambda = \frac{1}{f}\sqrt{\frac{E}{\rho}}$, where f is the desired frequency, *E* is the Young's modulus of the material, and ρ is the density of the material. Here the variation of acoustic impedances is realized by periodically varying mechanical properties of materials. Another possible realization is through the periodical variation of the size of the beam cross-sections. For example, FIG. 7 and FIG. 8 show resonators confined between acoustic mirrors which comprise the same materials with periodical variation of the beam width. This kind of one-dimensional extensional resonator configuration can be fabricated by using

various microfabrication methods, such as micromachining technologies which include patterning such as photolithography, and pattern transfer processes such as etching and lift-off (see, for example, Madou, Marc J., "Fundamentals of Microfabrication: The Science of Miniaturization", Second Edition, CRC Press, incorporated herein by reference). Two acoustic mirrors at these two ends of the beam can be used as anchors to the substrates.

[0038] As can be seen from FIG. 4A, the resonator of extension modes is placed between two structures with alternating varying acoustic impedance, called acoustic mirrors. As can be seen from FIG. 4B, acoustic waves within certain wavelength or frequency ranges which are incident on the acoustic mirrors can be totally reflected. The side-lobes of the reflectivity as seen in FIG. 4B are from the finite numbers layers of an acoustic mirror, which can be minimized by increasing the layers in the acoustic mirrors. Even for acoustic mirrors of finite layers, the side-lobes can be diminished by apodizing the period of the acoustic mirrors as have been commonly used in optical grating filters. Therefore, if the resonant frequency of the resonator 102 is designed to fall within this frequency range, all acoustic or mechanical energy at resonant frequencies can be confined, while for other frequencies, mechanical energy still goes to the substrate or anchoring structures, and no resonance will result.

[0039] It will be appreciated that the example shown in FIG. 4 is one-dimensional. However, this technique can also be extended to two-dimensions. FIG. 5 illustrates an example of a two-dimensional extensional resonator structure 200. In the embodiment shown, the resonator 202 in the central area is surrounded by a periodic array of holes 204, which can alternatively comprise periodical variations of material having different mechanical properties. The symmetry, shapes of the holes or periodic material variations, as well as the center resonator area, can be designed according to specific device requirements. Furthermore, the holes can optionally contain acoustic crystals. The entire structure can be easily suspended by anchors *A*.

[0040] With the hole-array surrounding the resonator, low frequency acoustic

waves falling within the resonant bandwidth of the resonator will be confined to the resonator area. Furthermore, high frequency waves with wavelengths less than the spacing between the holes will pass through the hole-array to the outside or the substrate to which the structure is suspended.

[0041] Referring again to FIG. 1, as well as to FIG. 6, the transducer, which is an important part of the microelectromechanical high-pass filter, can be realized by using piezoelectric materials such as ZnO or AlN. The transducer configuration illustrated comprises a top electrode, a bottom electrode, and piezoelectric material film in-between the electrodes, and many times a thin dielectric material layer such as SiO_2 deposited respectively between the piezoelectric and two electrodes to prevent leaky current. For example, a piezoelectric membrane can be micromachined with hole-arrays and patterned with microelectrodes. The input signal $V_i(\omega)$, such as the one illustrated in FIG. 3, is then applied to a first electrode pair, and the output signal $V_o(\omega)$ after filtering will be measured at a second electrode pair.

[0042] Accordingly, the device illustrated in FIG. 1 and in more detail in FIG. 6 will function in a vacuum as a micromechanical high-pass filter for radio frequency signal processing. Electrical signals from an antenna or electrical circuits are input to the electrode pair 22a, 22b, and converted to longitudinal acoustic waves along the membrane 16 which are then filtered through the two-dimensional hole-array as a high-pass filter. The electrode pair 24a, 24b detects the transmitted acoustic waves and converts them to electric signals as a function of the capacitance variations with the mechanical vibration amplitude.

[0043] Note also that, if holes 20 are filled with a material 26 having different mechanical properties than membrane 16, or if holes 20 are instead periodic variations of material having different mechanical properties than membrane 16, the hole arrays will act as acoustic crystals (very similar to photonic crystals), and the device design shown in FIG. 1 and FIG. 6 will act as a band-pass filter. The bandwidth depends on the contrast of mechanical properties of these two materials, and on the array parameters. The center frequency will

depend on the periodicity of the arrays.

[0044] Note further that the acoustic impedance of extensional beams depends not only on the material properties, but also on their cross-sectional area. Therefore, by using a beam of periodically varying cross section areas, one can build an acoustic mirror with one material, which makes the fabrication very robust and tolerable.

[0045] Referring now to FIG. 7, a filter structure 300 comprising a micro-resonator 302 suspended between two acoustic mirrors 304, 306 is illustrated. The extensional vibration mode of the resonator can be excited by using piezoelectric material to fabricate the resonator. Two building elements of the acoustic mirrors (narrow ones and wide ones) should be of a quarter of the acoustic wavelength at the desired resonant frequency (f): $\lambda/4 = \sqrt{E/\rho}/4f$, and the center resonator should be half of the acoustic wavelength of resonant frequency (f): $\lambda/2 = \sqrt{E/\rho}/2f$, where E is the Young's modulus of the material, and ρ is the density of the material. Similar to the high-pass filter, for better energy conversion or high electromechanical coupling, active piezo-materials such as zinc-oxide (ZnO), aluminum nitride (AlN), lead zirconate titanate (PZT), etc., can be used for the filters. The resonator structures can, for example, either be made of pure piezomaterials, or multilayers of dielectric, piezoelectric, and dielectric materials. The preferred approach is to have symmetrical materials layers in respect to the piezomaterial layers, so as to eliminate the excitation of flexural vibrations.

[0046] For example, the membrane can be constructed using the following process: (1) patterning of the bottom electrodes for transducers 12 and 14 using, for example, microphotolithography and lift-off processes (a common practice in microfabrication) on a silicon-on-insulator (SOI) wafer; (2) deposition of a dielectric layer of SiO_2; (3) deposition of a piezoelectric layer of ZnO; and (4) deposition of another layer of dielectric layer of SiO_2; (4) patterning of top electrodes for transducers 12 and 14 as in step (1); (5) patterning and etching to form the final structures of the resonators; and (6) releasing and suspending the membrane by etching the sacrificial layer Si (the

top layer of the substrate). The cut-of frequency depends on the film thicknesses. For example, when the piezoelectric ZnO layer is much thicker than the SiO_2 layers, then the cut-off frequency will mainly determined by the acoustic properties of the piezoelectric layer. On the other hand, when the SiO_2 layers are much thicker than the piezoelectric ZnO layer, then the cut-off frequency will mainly determined by the acoustic properties of the SiO_2 layers.

[0047] Microresonators can also be coupled together in a way such as illustrated in FIG. 8 which shows an embodiment of a band-pass filter 400 comprising micro-resonators 402, 404 suspended between acoustic mirrors 406, 408, 410. By tuning the coupling efficiency, the resonant mode of these two resonators can be tuned to form a narrow-band band-pass filter. Tuning the coupling efficiencies between resonators can be realized by varying the geometrical parameters. Tuning the coupling efficiencies between resonators can be realized by varying the geometrical parameters. As shown in FIG. 8, the coupling element 408 between resonators 402, 404 comprises two wide elements 408a, 408b and one narrow element 408c of acoustic mirrors. For example, to increase the coupling efficiencies, one can either decrease the coupling elements to only one wide element, or decrease the length of the narrow element 408c. Similarly, to decrease the coupling efficiencies, one can either increase the coupling elements, or increase the length of the narrow element 408c. By implementing more than two resonators and making them coupled with designed coupling coefficients, various band pass filter configurations can be realized. Note also that this one-dimensional coupled resonator can be extended to a two-dimensional case by using the periodical arrays of holes or materials of different mechanical properties as illustrated in FIG. 5. The electromechanical coupling can be realized by using piezoelectric materials in a similar way for high pass filters described in the above.

[0048] Although the description above contains many details, these should not be construed as limiting the scope of the invention but as merely providing illustrations of some of the presently preferred embodiments of this invention. Therefore, it will be appreciated that the scope of the present invention fully encompasses other embodiments which may become obvious to those skilled

in the art, and that the scope of the present invention is accordingly to be limited by nothing other than the appended claims, in which reference to an element in the singular is not intended to mean "one and only one" unless explicitly so stated, but rather "one or more." All structural, chemical, and functional equivalents to the elements of the above-described preferred embodiment that are known to those of ordinary skill in the art are expressly incorporated herein by reference and are intended to be encompassed by the present claims. Moreover, it is not necessary for a device or method to address each and every problem sought to be solved by the present invention, for it to be encompassed by the present claims. Furthermore, no element, component, or method step in the present disclosure is intended to be dedicated to the public regardless of whether the element, component, or method step is explicitly recited in the claims. No claim element herein is to be construed under the provisions of 35 U.S.C. 112, sixth paragraph, unless the element is expressly recited using the phrase "means for."

CLAIMS

What is claimed is:

1. A filter apparatus, comprising:

a membrane, said membrane comprising a first material;

said membrane including a plurality of spaced-apart periodic variations forming an array;

wherein acoustic waves incident on said membrane having a wavelength greater than the spacing between said periodic variations are attenuated; and

wherein acoustic waves incident on said membrane having a wavelength less than the spacing between said periodic variations pass through said membrane.

2. An apparatus as recited in claim 1, wherein said periodic variations comprise holes.

3. An apparatus as recited in claim 1, wherein said holes are filled with a second material having properties different than said first material.

4. An apparatus as recited in claim 1, wherein said periodic variations comprise a second material in said membrane that has different properties than said first material.

5. An apparatus as recited in claim 1, wherein for wavelengths greater than the spacing between said periodic variations in said array, the incident waves can only tunnel through the array by surface states.

6. An apparatus as recited in claim 1, further comprising:

an input transducer coupled to said membrane;

an output transducer coupled to said membrane;

wherein said input transducer is configured to convert electrical signals into acoustic waves along said membrane; and

wherein said output transducer is configured to convert acoustic waves which

have passed through said membrane to electrical signals.

7. An apparatus as recited in claim 1, wherein increasing the number of periodic variations in said array produces sharper, step-function-like, filter characteristics.

8. An apparatus as recited in claim 1, further comprising:

an acoustic resonator;

said resonator surrounded by said array of periodic variations;

wherein acoustic waves having a resonance frequency within a range of resonant frequencies of said resonator are confined by said resonator.

9. A filter apparatus, comprising:

a membrane;

said membrane including a plurality of spaced-apart holes forming an array;

wherein acoustic waves incident on said membrane having a wavelength greater than the spacing between said holes are attenuated; and

wherein acoustic waves incident on said membrane having a wavelength less than the spacing between said holes pass through said membrane.

10. An apparatus as recited in claim 9:

wherein said membrane comprises a first material; and

wherein said holes are filled with a second material having properties different than said first material.

11. An apparatus as recited in claim 9, wherein for wavelengths greater than the spacing between said holes in said array, the incident waves can only tunnel through the array by surface states.

12. An apparatus as recited in claim 9, further comprising:

an input transducer coupled to said membrane;

an output transducer coupled to said membrane;

wherein said input transducer is configured to convert electrical signals into acoustic waves along said membrane; and

wherein said output transducer is configured to convert acoustic waves which have passed through said membrane to electrical signals.

13. An apparatus as recited in claim 9, wherein increasing the number of holes in said array produces sharper, step-function-like, filter characteristics.

14. An apparatus as recited in claim 9, further comprising:

an acoustic resonator;

said resonator surrounded by said array of holes;

wherein acoustic waves having a resonance frequency within a range of resonant frequencies of said resonator are confined by said resonator.

15. A filter apparatus, comprising:

a membrane;

said membrane including a plurality of spaced-apart holes forming an array;

an acoustic resonator;

said resonator surrounded by said array of holes;

wherein acoustic waves having a resonance frequency within a range of resonant frequencies of said resonator are confined by said resonator;

wherein acoustic waves incident on said membrane having a wavelength greater than the spacing between said holes are attenuated; and

wherein acoustic waves incident on said membrane having a wavelength less than the spacing between said holes pass through said membrane.

16. An apparatus as recited in claim 15:

wherein said membrane comprises a first material; and

wherein said holes are filled with a second material having properties different than said first material.

17. An apparatus as recited in claim 15, wherein for wavelengths greater than the spacing between said holes in said array, the incident waves can only tunnel through the array by surface states.

18. An apparatus as recited in claim 15, further comprising:

an input transducer coupled to said membrane;

an output transducer coupled to said membrane;

wherein said input transducer is configured to convert electrical signals into acoustic waves along said membrane; and

wherein said output transducer is configured to convert acoustic waves which have passed through said membrane to electrical signals.

19. An apparatus as recited in claim 15, wherein increasing the number of holes in said array produces sharper, step-function-like, filter characteristics.

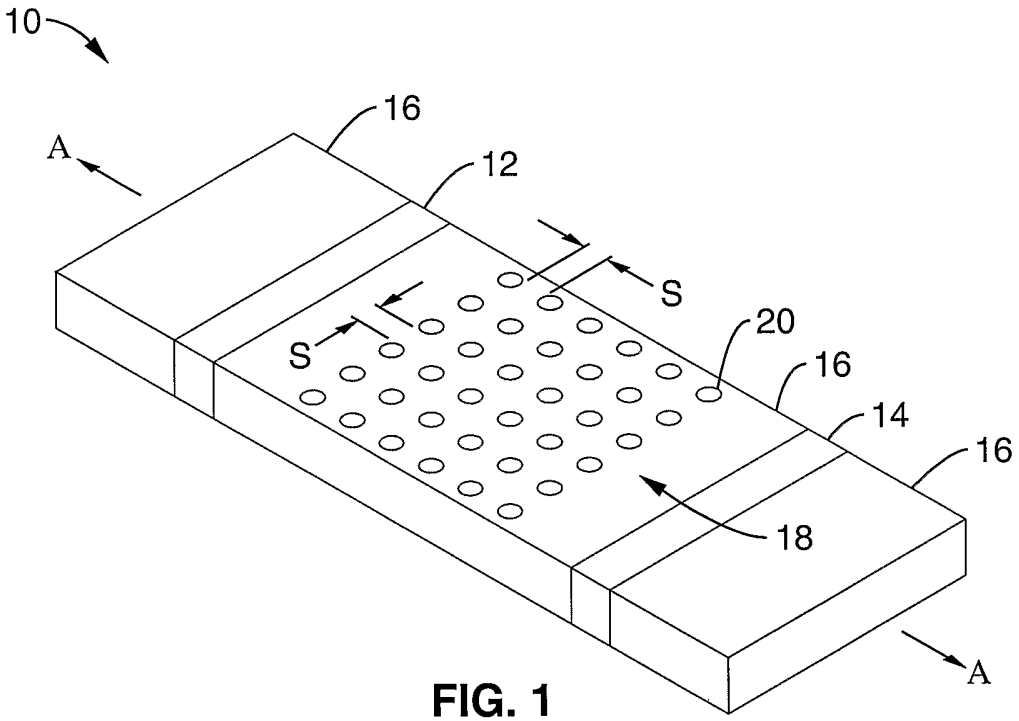


FIG. 1

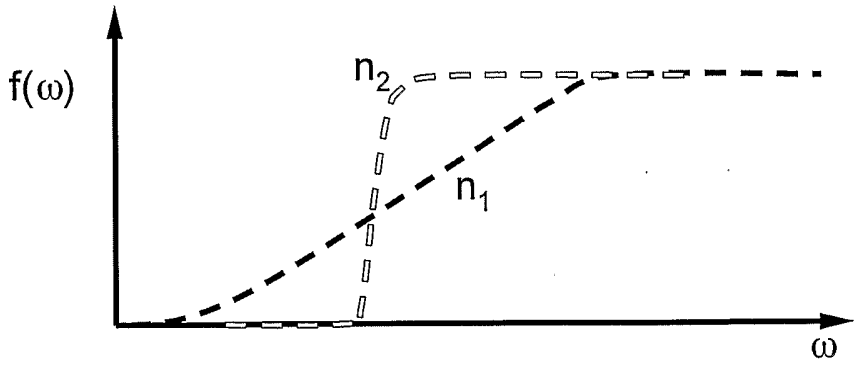


FIG. 2

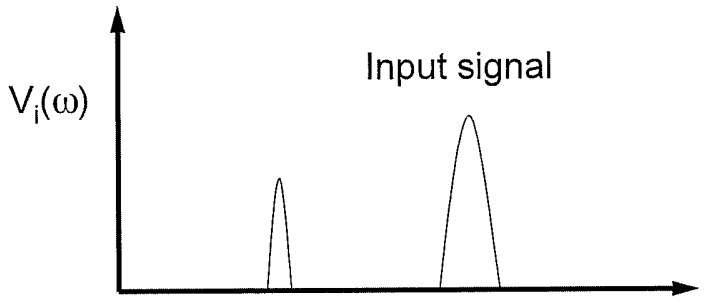


FIG. 3A

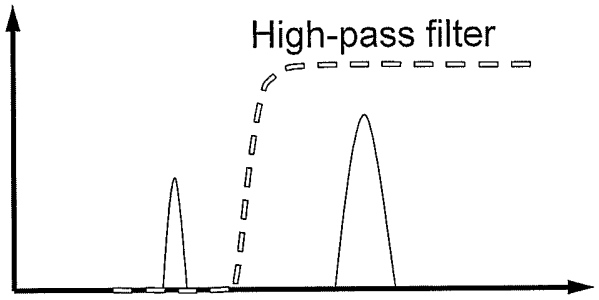


FIG. 3B

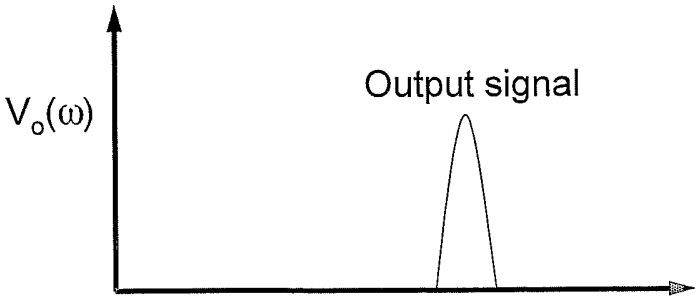


FIG. 3C

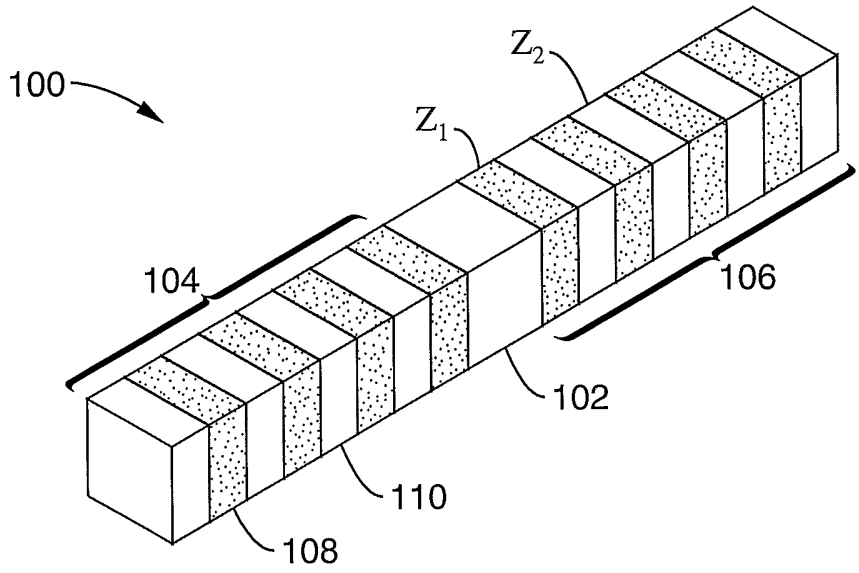

100
Z_2
Z_1
104
106
102
110
108

FIG. 4A

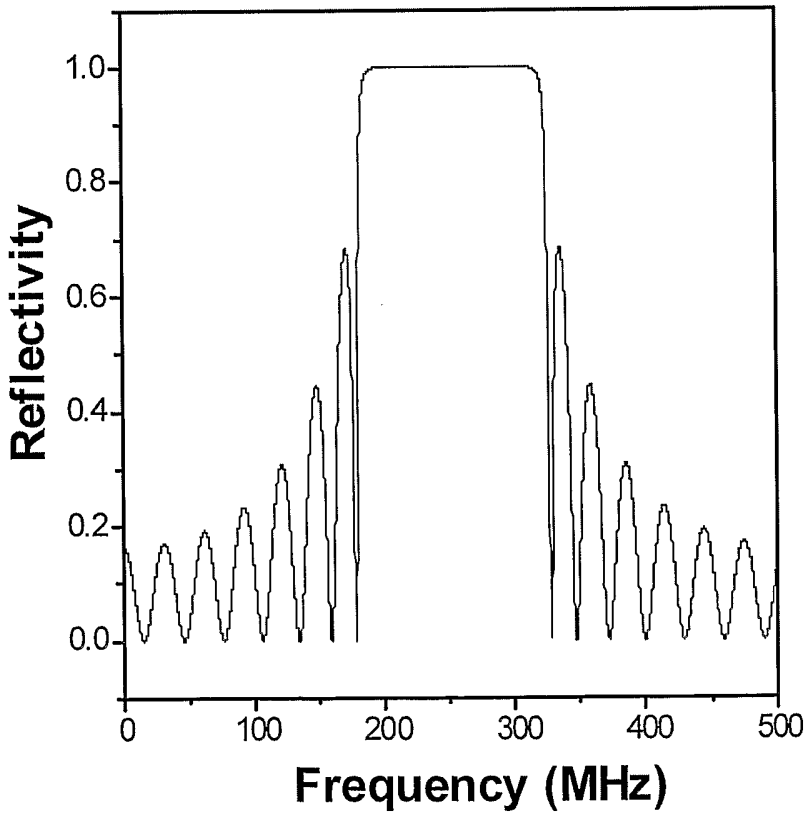

Reflectivity
1.0
0.8
0.6
0.4
0.2
0.0
0
100
200
300
400
500
Frequency (MHz)

FIG. 4B

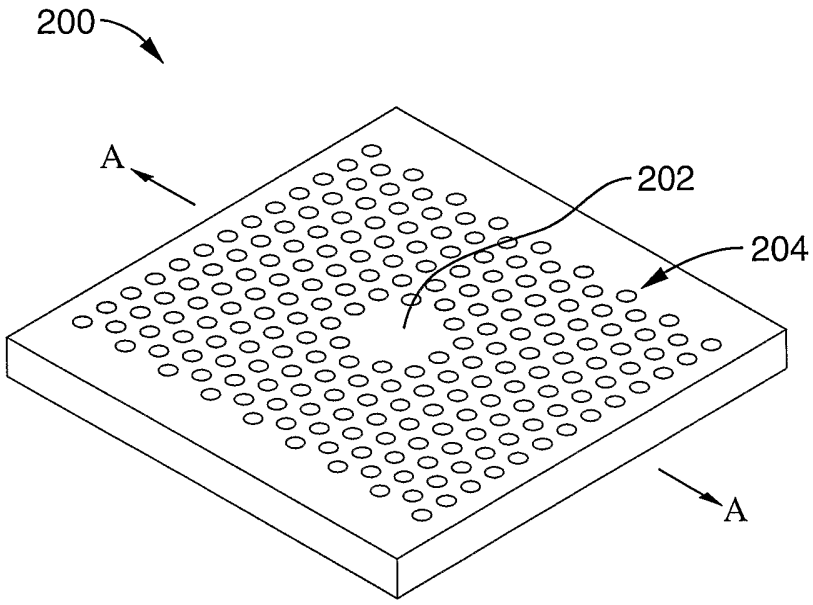


FIG. 5

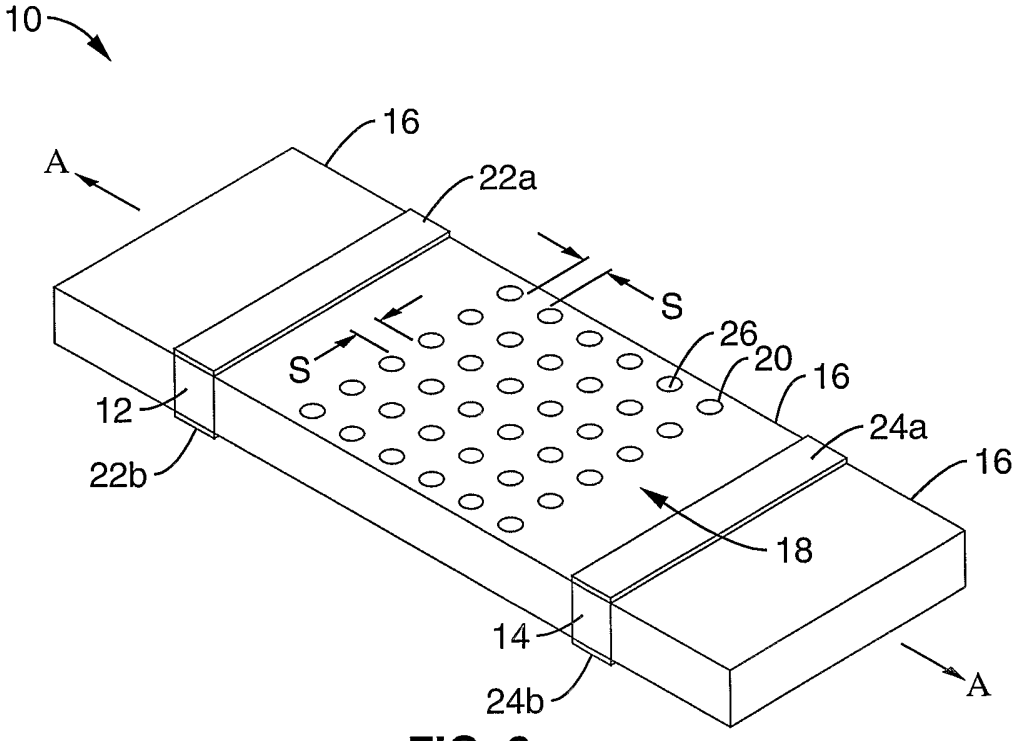


FIG. 6

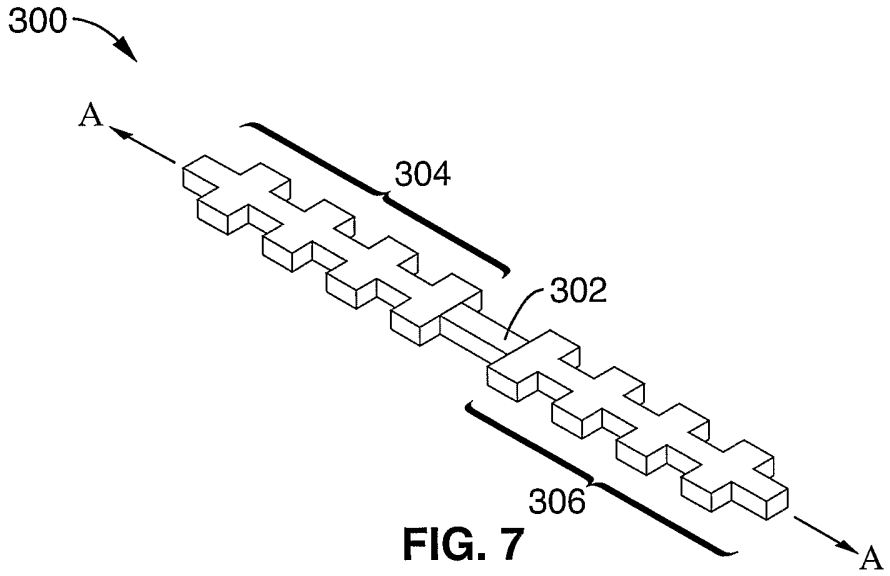


FIG. 7

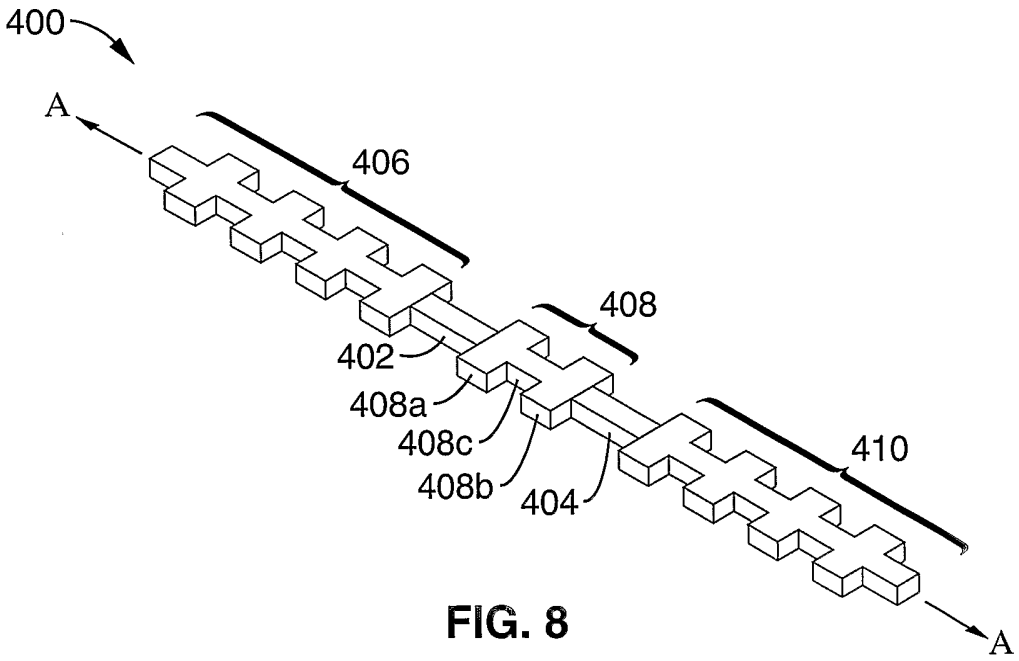


FIG. 8