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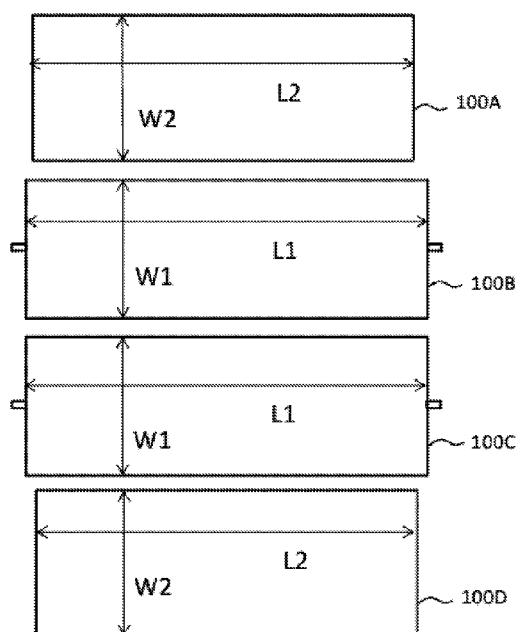


Fig. 5A

(57) Abstract: A MEMS resonator is provided with improved electrical characteristics and reduced spurious resonances. The MEMS resonator includes two or more first rectangular resonator plates with lengths greater than their respective widths. Moreover, the MEMS resonator includes two or more second rectangular resonator plates that are positioned parallel to the first resonator plates in the width-wise direction of the MEMS resonator. The length of the second resonator plates is different than the length of the first resonator plates to reduce spurious resonances.



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MEMS RESONATOR WITH SUPPRESSED SPURIOUS MODES

FIELD OF THE INVENTION

[0001] The present invention relates generally to a MEMS resonator, and, more particularly, to a MEMS resonator with reduced spurious modes.

BACKGROUND OF THE INVENTION

[0002] Microelectromechanical system ("MEMS") resonators are small electromechanical structures that vibrate at high frequencies and are often used for timing references, signal filtering, mass sensing, biological sensing, motion sensing, and other applications. MEMS resonators are considered a common alternative to quartz timing devices to provide an accurate time or frequency reference. In general, quartz resonators have a high quality factor and piezoelectric coupling. High quality factor indicates a low rate of energy loss relative to the stored energy of the resonator, i.e., the oscillations die out more slowly. However, one limitation for quartz resonators is that they are difficult to design in smaller sizes.

[0003] Typically, MEMS resonators are made of silicon using lithography based manufacturing processes and wafer level

processing techniques. Designers and manufacturers have found that pure silicon resonators often demonstrate very high quality factors comparable to quartz crystals. However, bare silicon is not piezoelectric and pure silicon resonators have high motional impedance making them unsuitable to replace quartz resonators in many applications.

[0004] In order to lower the motional impedance of MEMS resonator, some designs have added piezoelectric material, such as a layer of thin film of aluminum nitride (AlN). A typical piezoelectric micromechanical resonator is shown in Figs. 1A and 1B.

[0005] In particular, Fig. 1A illustrates a top view of a conventional resonator 10 that is rectangular shaped and includes two smalls anchor 11A and 11B on the sides of the resonator to mount the resonator.

[0006] Fig. 1B illustrates a cross sectional view of the conventional resonator 10. Typically, the resonator 10 is manufactured of silicon using MEMS manufacturing techniques. On top of silicon substrate 12, the resonator 10 has a piezoelectric thin film 16 sandwiched between two metal electrodes 14A and 14B to provide piezoelectric coupling. In an exemplary design, the metal electrodes 14A and 14B are typically

molybdenum, but other materials such as platinum or aluminum may also be used. Moreover, the piezoelectric film 16 may be aluminum nitride (AlN) or doped aluminum nitride, but may also be PZT or titanium oxide.

[0007] In conventional designs, the thickness of the metal electrodes 14A and 14B is typically 50 nanometers (nm) to 400 nm and the thickness of the piezoelectric film 16 is typically 400 nm to 2 μm . Moreover, the thickness of the silicon substrate 12 may range from 3 μm to 30 μm , for example. Although not shown, additional thin film layers may also be present in some conventional designs. For example, a layer of silicon dioxide thin film can be used to change the temperature coefficient of frequency of the resonator.

[0008] To maximize the resonator quality factor, resonators are preferably designed to resonate in a bulk mode where the resonator deforms mainly in the in-plane vibration mode where the out-of-plane movement is minimized. In particular, it is desirable that out-of-plane bending modes of the resonator are avoided since these modes have low quality factors at high frequencies.

[0009] In general, lateral dimensions of resonators will determine the resonator's resonance frequency and are also

important in designing high quality factor resonators. Typically, a resonator with a high quality factor has a rectangular shape with width W and length L, for example as shown in Fig. 2. In particular, Fig. 2 illustrates a top view of a width extensional resonator 10 according to a conventional design. As shown, the vibrational motion of the resonator 10 is mainly in the width direction (i.e., contraction and expansion vibration). This width extensional mode is preferred since the anchoring points 11A and 11B on the short sides of the resonator have minimal movement, thereby minimizing the anchor losses and maximizing the quality factor.

[0010] Moreover, it is known that certain aspect ratios ("AR"), defined as the ratio of length L to width W (i.e., $AR = L/W$), minimize the mounting losses and therefore maximize the quality factor, for example, as described in Patent Document 1, identified below. In particular, an optimal aspect ratio ranges from 1.2 to 1.8 depending on material properties and is typically around 1.5 for silicon based resonators.

[0011] Furthermore, the resonance frequency is inversely related to the resonator width. Thus, as the width and length of the resonator 10 is reduced, the resonant frequency is correspondingly increased. However, the small size of such a

resonator will result in higher electrical impedance that is undesirable. One way to reduce the electrical impedance of a high frequency resonator is to increase the aspect ratio by an integer multiple N so that the aspect ratio is approximately $N \times 1.5$ (with 1.5 being an example of an optimal aspect ratio). For example, good choices for the aspect ratio are 1.5, 3.0, 4.5, 6.0, 7.5, and so on, with the exact value that minimizes the anchor movement being determined by simulation or experiments.

[0012] Moreover, the resonator impedance can be decreased even further by combining two or more rectangular shaped resonators along the long edge to make a higher order overtone resonator, as described in Non-patent Document 1, for example, identified below.

[0013] Fig. 3A illustrates a higher order overtone resonator according to a conventional design. As shown, the resonator design includes four plate resonators 10A, 10B, 10C and 10D, with the resonator outer shape for each resonator being rectangular with a length L and a width W that is selected to achieve an aspect ratio $AR = L/W = 6$. Moreover, Fig. 3B illustrates the resulting overtone resonator 20 according to the conventional design shown in Fig. 3A. As shown, the four resonators 10A-10D are connected and aligned along the long edge

with length L to make a fourth-order overtone width-extensional mode resonator. Although four resonators are shown for this design, the technique can be extended to even higher order, for example, where 50 or even 100 or more plates can be connected together in this manner. Of course, one obvious drawback of this approach is that as the overall resonator dimensions become large, which, in turn, increases the number of undesirable out-of-plate bending modes during operation. These modes may be close in frequency to the desired in-plane mode and can result in spurious impedance response.

[0014] Fig. 3C illustrates an electrode pattern for the overtone resonator 20 shown in Fig. 3B. As shown, resonators 10A and 10C share the same top electrode 22A (i.e., top electrode 1) and resonators 10B and 10D share another top electrode 22B (i.e., top electrode 2). It is known that many different electrode patterns can be employed, for example, as disclosed in Patent Document 2, identified below.

[0015] Figs. 4A and 4B illustrate graphs of exemplary electrical resonator responses. The electrical responses are shown as impedance to frequency. As shown, for example, a clean impedance curve is illustrated in Fig. 4A where one clear resonance is observed. In contrast, a spurious impedance curve

is shown in Fig. 4B where an additional spurious resonance is observed following the main resonance. This type of spurious response is due to bending modes near the main width-extensional mode and it is very detrimental to resonator performance in time and frequency applications. Moreover, the resonance frequency of the out-of-plate bending modes is sensitive to small manufacturing variations and it may not be possible to completely eliminate these modes around the main resonance by adjusting the resonator thickness and aspect ratio. In manufacturing, this may result in yield loss where some resonators work as desired and some resonators exhibit the undesirable spurious response.

[0016] Patent Document 1: U.S. Patent No. 5,548,180.

[0017] Patent Document 2: WO 2016/114237.

[0018] Non-patent Document 1: Ho, *et al.*, "High-order composite bulk acoustic resonators", Micro Electro Mechanical Systems, 2007. IEEE 20th International Conference on. IEEE, 2007.

SUMMARY OF THE INVENTION

[0019] Accordingly, the MEMS resonator disclosed herein is provided to improve electrical characteristics while reducing spurious resonances observed in conventional MEMS designs.

[0020] Thus, according to one aspect, a MEMS resonator is provided that includes a plurality of first resonator plates each having a width $W1$ and a length $L1$, wherein the length $L1 >$ the width $W1$; and a plurality of second resonator plates each having a width $W2$ and a length $L2$, wherein the length $L2 >$ the width $W2$. Moreover, the plurality of first resonator plates and the plurality of second resonator plates are disposed parallel to each other in a widthwise direction of the MEMS resonator, and the length $L1$ does not equal the length $L2$.

[0021] In a variation of this aspect, the plurality of second resonator plates comprise at least a pair of second resonator plates that are respectively disposed adjacent to outer sides in the widthwise direction of a pair of the plurality of first resonator plates.

[0022] In another variation of this aspect, the pair of first resonator plates are disposed adjacent to each other at respective inner sides in the widthwise direction of the first resonator plates, the inner sides being opposite to the outer sides.

[0023] In another variation of this aspect, the MEMS resonator comprises a symmetric shape such that the plurality of second

resonator plates are aligned symmetrically relative to the plurality of first resonator plates in the widthwise direction.

[0024] In another variation of this aspect, the length L2 of each of the second resonator plates is substantially equal to $0.98 \times$ the length L1 of the first resonator plates.

[0025] In another variation of this aspect, the width W1 of each of the first resonator plates is substantially equal to the width W2 of each of the second resonator plates.

[0026] In another variation of this aspect, the MEMS resonator further includes at least one third resonator plate having a length L3 that is not equal to the length L1 or the length L2.

[0027] In another aspect, a MEMS resonator is provided that includes a plurality of inner resonator plates each having a width W1 and a length L1 that is greater than the width W1, wherein the inner resonator plates are disposed adjacent to each other along respective first sides of the inner resonator plates; and a plurality of outer resonator plates each having a width W2 and a length L2 that is greater than the width W2, wherein at least a pair of the outer resonator plates are disposed adjacent to respective second sides of a pair of the inner resonator plates. In this aspect, the second sides of the pair of inner resonator plates are opposite the first sides,

respectively, in the widthwise direction of the MEMS resonator, and the length L1 does not equal the length L2.

[0028] In another aspect, a MEMS resonator is provided that includes a plurality of first resonator plates each being rectangular shaped and having a pair of longer sides with a length L1 and a pair of shorter sides with a width W1, wherein the length $L1 >$ the width W1; and a plurality of second resonator plates each having a pair of first sides extending in a direction parallel to each other and a pair of second sides connecting the pair of first sides, respectively, the pair of second sides not extending in a direction parallel to each other. In this aspect, the plurality of first resonator plates and the plurality of second resonator plates are disposed parallel to each other in a widthwise direction of the MEMS resonator.

[0029] The above simplified summary of example embodiments serves to provide a basic understanding of the present disclosure. This summary is not an extensive overview of all contemplated aspects, and is intended to neither identify key or critical elements of all aspects nor delineate the scope of any or all aspects of the present disclosure. Its sole purpose is to present one or more aspects in a simplified form as a prelude

to the more detailed description of the disclosure that follows. To the accomplishment of the foregoing, the one or more aspects of the present disclosure include the features described and particularly pointed out in the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0030] The accompanying drawings, which are incorporated into and constitute a part of this specification, illustrate one or more example embodiments of the present disclosure and, together with the detailed description, serve to explain their principles and implementations. The drawings provided are for illustrative purposes only and are therefore not drawn to scale.

[0031] Figs. 1A and 1B illustrate a conventional piezoelectric micromechanical resonator.

[0032] Fig. 2 illustrates a top view of a width extensional resonator according to a conventional design.

[0033] Fig. 3A illustrates a higher order overtone resonator according to a conventional design.

[0034] Fig. 3B illustrates a resonator according to the conventional design shown in Fig. 3A.

[0035] Fig. 3C illustrates an electrode pattern for the resonator shown in Fig. 3B.

[0036] Figs. 4A and 4B illustrate graphs of exemplary electrical resonator responses.

[0037] Figs. 5A and 5B illustrate a top view of a MEMS resonator according to an exemplary embodiment.

[0038] Figs. 5C and 5D provide graphs illustrating measured spurious responses that compare conventional designs shown in Fig. 3B, for example, with the exemplary overtone resonator shown in Fig. 5B.

[0039] Fig. 5E illustrates a graph that compares the length ratio of the lengths of the outer resonators with the lengths of the inner resonators.

[0040] Figs. 6A and 6B illustrate a top view of a MEMS resonator according to another exemplary embodiment.

[0041] Figs. 7A and 7B illustrate a top view of a MEMS resonator according to yet another exemplary embodiment.

[0042] Figs. 8A and 8B illustrate a top view of a MEMS resonator according to another exemplary embodiment.

DETAILED DESCRIPTION OF THE EXEMPLARY EMBODIMENTS

[0043] According to the exemplary embodiments described herein, MEMS resonator designs are provided to improve electrical

characteristics, such as quality factor, while reducing spurious resonances observed in conventional MEMS designs. In particular, the exemplary resonators have varied outer shapes of individual resonator plates used in constructing the overtone resonator. As a result, undesirable spurious modes are suppressed without affecting other critical resonator parameters such as quality factor. Moreover, by making the overtone resonator from individual resonators with slightly dissimilar outer shapes, the bending resonances are moved to other frequencies and the electrical coupling is reduced. For example, by varying the length of the individual rectangular plates that comprise the overtone resonator, the spurious modes are effectively suppressed.

[0044] Those of ordinary skill in the art will realize that the following description is illustrative only and is not intended to be in any way limiting. Other aspects will readily suggest themselves to those skilled in the art having the benefit of this disclosure. Reference will now be made in detail to implementations of the example aspects as illustrated in the accompanying drawings. The same reference indicators will be used to the extent possible throughout the drawings and the following description to refer to the same or like items.

[0045] Figs. 5A and 5B illustrate a MEMS resonator according to an exemplary embodiment. As shown, an overtone resonator 100 is provided that includes a plurality of individual resonator plates 100A, 100B, 100C and 100D. It is noted that the term "resonator plates" is used interchangeably with the concept of individual resonators for the MEMS overtone resonators disclosed herein. Accordingly, to the exemplary embodiment, each of the individual resonators 100A-100D comprises an outer shape that is substantially rectangular shaped. In general, it is contemplated that the term "substantially" as is used herein takes into account minor variations in the resonator shape that may occur during the manufacturing process. For example, according to one embodiment, the resonator plates 100A and 100D are designed to have identical or substantially identical dimensions, and the resonator plates 100B and 100C are designed to have identical or substantially identical dimensions. However, the machines uses to deposit and etch the layers during the MEMS manufacturing process may lead to slight differences in these dimensions. Thus, the term "substantially" takes into account resulting variances in dimensions due to variations in the manufacturing equipment.

[0046] Moreover, in one aspect, each of the resonator plates can be processed from the same layer of an SOI wafer (i.e., the structural layer). It should also be understood that while not shown, each of the resonator plates can include a piezoelectric thin film sandwiched between two metal electrodes to provide piezoelectric coupling, such as the conventional design shown in Fig. 1B. Moreover, according to an exemplary embodiment, the silicon surface is in the [001] crystal direction and the c-axis (i.e., the crystallographic axis) of the piezoelectric thin film is aligned along the thickness direction. Furthermore, the resonator plates can have an orientation with the width direction of the plate aligned either to the [100] silicon crystal direction or the [110] silicon crystal direction.

[0047] The metal electrodes can be formed by molybdenum, platinum or aluminum, for example. Moreover, the resonator plates are coupled in parallel according to electrical connections, such as the design illustrated in Fig. 3C, and discussed above. The specific electrical connection configuration is not critical to the exemplary MEMS resonators disclosed herein and will not be described in further detail.

[0048] In any event, resonator plates 100A and 100D can be considered "outer" resonators and a first pair of resonator

plates, while resonator plates 100B and 100C can be considered "inner" resonators and a second pair of resonator plates. According to the exemplary embodiment, the inner resonator plates 100B and 100C have length $L1 = 6 \times W1$, i.e., the aspect ratio is 6. Moreover, the outer resonator 100A and 100D have a slightly narrower length $L2 = 0.98 \times L1$ but the same width $W2 = W1$ as inner resonator plates 100B and 100C. The four plates 100A-100D preferably have the same or substantially the same resonance frequency and, therefore, the plate widths of resonator plates 100A-100D should be equal or substantially equal to each other (i.e., $W1 = W2$), according to an exemplary embodiment.

[0049] As shown above in Fig. 5B, these four individual resonator plates 100A-100D are connected along the lengths of the inner resonator plates 100B and 100C to make an overtone resonator 100 according to an exemplary embodiment. More particularly, resonator plate 100A has parallel long sides 102A and 104A and parallel shorter sides 106A and 108A. Similarly, resonator plate 100B has parallel long sides 102B and 104B and parallel shorter sides 106B and 108B, resonator plate 100C has parallel long sides 102C and 104C and parallel shorter sides

106C and 108C, and resonator plate 100D has parallel long sides 102D and 104D and parallel shorter sides 106D and 108D.

[0050] As shown, each of resonator plates 100A-100D are positioned in parallel to each other in the widthwise direction of the MEMS resonator 100. Thus, the long side 104A of resonator plate 100A is disposed adjacent to and parallel to long side 102B (i.e., the "outer" side) of resonator plate 100B, the long side 104B (i.e., the "inner" side) of resonator plate 100B is disposed adjacent to and parallel to long side 102C (i.e., the "inner" side) of resonator plate 100C, and the long side 104C (i.e., the "outer" side) of resonator plate 100C is disposed adjacent to and parallel to long side 102D of resonator plate 100D.

[0051] Furthermore, the shorter sides (extending in the width direction) of resonator plates 100B and 100C are not aligned with the shorter sides of resonator plates 100A and 100D. In other words, sides 106B and 106C are aligned with each other and sides 108B and 108C are aligned with each other. However, these sides are not aligned with sides 106A and 106D or 108A and 108D in the widthwise direction. As will be described in more detail below, due to the exemplary design with the resonator plates

100A-100D having varying lengths, the overtone resonator 100 is less susceptible to spurious responses.

[0052] As further shown, resonator plate 100B includes anchoring points 110 and 111 and resonator plate 100C includes anchoring points 112 and 113. Preferably, these anchoring points 110-113 are physically coupled to a frame (i.e., a support member) of the sensor device (not shown), such that the overtone resonator 100 is disposed in a cavity therein, as would be appreciated to one skilled in the art. Moreover, the anchoring points 110-113 are nodal points of vibration expansion in the width expansion mode, as described above. Thus, as shown, the respective anchoring points are positioned at the center of each major surface of resonator plates 100B and 100C, respectively, and at central portions of the sides 106B, 106C, 108B and 108C.

[0053] It should be appreciated that while the inner resonator plates 100B and 100C are shown to have a longer length L_1 than the length L_2 of outer resonator plates 100A and 100D, and are shown to be centered relative to the outer resonator plates 100A and 100D, variations of this configuration can be employed according to alternative embodiments. For example, the resonators with shorter length (i.e., resonator plates 100A and

100D) may be in the center of overtone resonator 100 (i.e., as the "inner" resonator plates) with the longer resonator plates 100B and 100C as the "outer" resonators. Moreover, the longer and shorter resonator plates may be alternating in position according to another embodiment, i.e., resonator 100A, then resonator 100B, then resonator 100D, and then resonator 100C can be positioned in sequence. However, the overtone resonator 100 preferably has a symmetrical design as shown in Fig. 5B.

[0054] According to an exemplary embodiment, the overtone resonator 100 is a 96-MHz resonator that has dimensions of $W1 = W2 = 40 \mu\text{m}$ and lengths $L1 = 240 \mu\text{m}$ and $L2 = 0.98 \times L1 = 235 \mu\text{m}$. In this embodiment, the variation in the plate lengths $L1$ and $L2$ does not disturb the desired width extensional-mode, but suppresses the undesirable bending modes.

[0055] Accordingly, while the range of length ratios may vary according to the exemplary design, the ratio is preferably provided as follows:

$$0.001 < \left| \frac{L1}{L2} - 1 \right| < 0.1$$

and more preferably limited as follows:

$$0.002 < \left| \frac{L1}{L2} - 1 \right| < 0.05.$$

[0056] Figs. 5C and 5D provide graphs illustrating measured spurious responses that compare conventional designs with the exemplary overtone resonator 100 described above. In particular, Fig. 5C illustrates a wafer map with measured impedance curves for conventional resonators (e.g., the design of Fig. 3B). As shown, more than half of the resonators manufactured would experience a spurious response (i.e., the spurious response shown in Fig. 4B). In contrast, Fig. 5D illustrates a wafer map with measured impedance curves for the exemplary resonators with the length L_2 equals $0.98 \times$ length L_1 , as described above (i.e., the design of Fig. 5B). As shown, the exemplary design produces almost all resonators that do not experience spurious responses and rather have a clean response, such as that shown in Fig. 4A.

[0057] Fig. 5E illustrates a graph that compares the length ratio of the lengths of the outer resonator plates 100A and 100D (i.e., lengths L_2) with the lengths of the inner resonator plates 100B and 100C (i.e., lengths L_1). Specifically, the graph of Fig. 5E illustrates how this ratio L_2/L_1 effects the electromechanical coupling coefficient percentage. As shown when the ratio of L_2/L_1 is less than approximately 0.96 or greater than approximately 1.02, the coupling coefficient drops

significantly indicating poor resonance vibration mode. In other words, a larger difference in the respective aspect ratios of the outer resonator plates 100A and 100D to the inner resonator plates 100B and 100C (and vice versa) would substantially disturb the desired width extensional mode resulting in a low quality factor.

[0058] Therefore, it should be appreciated that according to the exemplary embodiment $L2/L1$ should be greater than or equal to 0.96, but less than or equal to 1.02. As noted above, to also minimize spurious resonances, the length $L2$ does not equal length $L1$, but rather length $L2$ equals 0.98 times length $L1$ (and vice versa). A small difference would not effectively suppress the spurious modes while too large a difference would weaken the electrical characteristics of the desired mode.

[0059] As further described above, although the widths $W1$ and $W2$ can vary in some designs, according to the exemplary embodiment the widths $W1$ and $W2$ are equal or substantially equal so that the individual resonator plates 100A-100D used to construct the overtone resonator 100 have approximately the same resonant frequency. For example, in one embodiment, an exemplary range for width ratios is:

$$\left| \frac{W1}{W2} - 1 \right| < 0.1.$$

[0060] Figs. 6A and 6B illustrate a top view of a MEMS resonator according to another exemplary embodiment. As shown, an overtone resonator 200 is provided that includes a plurality of individual resonator plates 200A, 200B, 200C and 200D. According to the exemplary embodiment, inner resonator plates 200B and 200C are substantially rectangular shaped with widths W1 and lengths L1. For example, resonator plate 200B has long sides 202B and 204B each have a length L1 and shorted sides 206B and 208B each having a length equal to the width W1. Similarly, resonator plate 200C has long sides 202C and 204C each have a length L1 and shorted sides 206C and 208C each having a length equal to the width W1.

[0061] Moreover, the geometry or shape of the resonator plates 200A and 200D is slightly varied compared with the overtone resonator 100 in that resonator plates 200A and 200D each comprise a trapezoid shaped with width W2. As shown in Fig 5B, for example, the longer length of resonator 200A (i.e., the inner side 204A disposed adjacent to the side 202B of resonator 200B) is the same length of resonator 200B, which is length L1. However, the outer side (i.e., side 202A) has a length of L2

that is shorter than length L1. Similarly, the longer side 202D of resonator 200D (i.e., the inner side positioned to the side 204C of resonator 200C) is the same length of resonator 200C, which is also length L1. However, the outer side 204D of resonator 200D has a length of L2 that is shorter than length L1. As a result, while sides 202A and 204A of resonator plate 200A extend in a parallel direction, sides 206A and 208A taper inward in the widthwise direction towards each other and, therefore, are not parallel to one another. Resonator plate 200D has the opposite configuration such that the overtone resonator 200 comprises an overall symmetrical shape in the widthwise direction.

[0062] According to the exemplary embodiment, the average length of the two trapezoid shaped resonator plates 200A and 200D is equal to $L2a = (L1+L2)/2$. Moreover, the four resonator plates 200A-200D shown in in Fig. 6A are connected or positioned adjacent to each other as shown in Fig. 6B to make the exemplary overtone resonator 200. According to the exemplary embodiment, the length ratio defined in terms of the average length as L2a preferably satisfies the following:

$$0.001 < \left| \frac{L1}{L2a} - 1 \right| < 0.1.$$

[0063] In one aspect, it is noted that while each of the exemplary overtone resonators 100 and 200 described above are comprised of four individual resonators, the exemplary designs can be composed of four or more than four individual resonators to obtain the desired improved electrical characteristics, such as quality factor, while reducing and/or eliminating spurious resonances.

[0064] For example, Figs. 7A and 7B illustrate a top view of a MEMS resonator according to yet another exemplary embodiment. As shown in Fig. 7A, the overtone resonator 300 is formed from five individual resonator plates 300A, 300B, 300C, 300D and 300E, with each resonator have a corresponding length and width. More particularly, resonator 300A has a length L_1 and width W_1 , resonator 300B has a length L_2 and width W_2 , resonator 300C has a length L_3 and width W_3 , resonator 300D has a length L_4 and width W_4 , and resonator 300E has a length L_5 and width W_5 . As shown, each of the resonator plates 300A-300D have a substantially rectangular shape and are connected to each other along the longer sides as shown in Fig. 7B to form the overtone resonator 300.

[0065] According to an exemplary embodiment, the overtone resonator 300 has a symmetrical design in that at least length L2 of resonator 300B and length L4 of resonator 300D are equal to each other. Moreover, at least length L1 of resonator 300A and length L5 of resonator 300E are equal to each other. Furthermore, according to the exemplary embodiment, length L3 is preferably longer than length L1 and length L5, but shorter than length L2 and length L4. In this regard, the current embodiment can be applied to arbitrarily large overtone resonator (in terms of number of individual resonators) as long as at least a portion of the adjacent resonators satisfy the length criteria:

$$0.001 < \left| \frac{L_i}{L_{i+1}} - 1 \right| < 0.1,$$

[0066] In this embodiment, L_i and L_{i+1} are average lengths of adjacent resonators. That is L_i can represent length L1 and L_{i+1} can represent length L2 or L_i can represent length L2 and L_{i+1} can represent length L3, and so forth. Thus, the absolute value of the ratio of lengths of adjacent ratios minus 1 should be between 0.001 and 0.1 in this aspect in order to minimize spurious resonance. Moreover, according to this embodiment, the widths W1-W5 of the individual resonator plates 300A-300E are preferably equal or substantially equal so that the individual

resonators used to construct the overtone resonator 300 have approximately the same resonant frequency.

[0067] Figs. 8A and 8B illustrate a top view of a MEMS resonator according to another exemplary embodiment. As shown, the MEMS resonator includes the same design of Figs. 6A and 6B in that a first pair of resonator plates 400B and 400C are rectangular shaped with width $W1$ and length $L1$. Moreover, the long sides of these resonator plates extend parallel to each other. Similarly, the long sides of resonator plates 400A and 400D are also parallel and have the same length $L1$ as resonator plates 400B and 400C.

[0068] However, as further shown, the shorter sides of resonator plates 400A and 400D are not parallel to each other, but instead have concave sides directed inward. For example, the four resonator plates 400A through 400D are combined as shown in Fig. 8B to form a fourth-order overtone resonator 400. However, the shorter sides of resonator plate 400A include inward tapered sides portions 401A and 402A and outward tapered side portions 403A and 404A. Thus, the length of the resonator plate 400A narrows from length $L1$ to length $L2$ at its narrowest point before tapering outward. Similarly, the shorter sides of resonator plate 400D include inward tapered sides portions 401D

and 402D and outward tapered side portions 403D and 404D. Thus, the length of the resonator plate 400D also narrows from length L1 to length L2 at its narrowest point before tapering outward.

[0069] According to the exemplary embodiment, the average length of the resonator plates 400A and 400D is $L2a = (L1+L2)/2$. In this case, the length ratio defined in terms of the average length as L2a and in exemplary embodiment satisfies the following:

$$0.001 < \left| \frac{L1}{L2a} - 1 \right| < 0.1.$$

[0070] It should be appreciated that many different outer shapes are possible for the short side of the individual resonator plates 400A and 400D, including but not limiting to concave shapes and convex shapes. Thus, while straight linear side portions are shown as 401A-404A and 401D-404D, these sides can be curved in a convex or concave design in an alternative embodiment. Moreover, according to this embodiment, the widths W1 and W2 of the individual resonator plates 400A-400D are preferably equal or substantially equal so that the individual resonators used to construct the overtone resonator 400 have approximately the same resonant frequency.

[0071] In the interest of clarity, not all of the routine features of the embodiments are disclosed herein. It should be appreciated that in the development of any actual implementation of the present disclosure, numerous implementation-specific decisions must be made in order to achieve the designer's specific goals, and these specific goals will vary for different implementations and different designers. It is understood that such a design effort might be complex and time-consuming, but would nevertheless be a routine undertaking of engineering for those of ordinary skill in the art, having the benefit of this disclosure.

[0072] Furthermore, it is to be understood that the phraseology or terminology used herein is for the purpose of description and not of restriction, such that the terminology or phraseology of the present specification is to be interpreted by those skilled in the art in light of the teachings and guidance presented herein, in combination with the knowledge of the skilled in the relevant art(s). Moreover, it is not intended for any term in the specification or claims to be ascribed an uncommon or special meaning unless explicitly set forth as such.

[0073] While the foregoing has been described in conjunction with exemplary embodiments, it is understood that the term

"exemplary" is merely meant as an example. Accordingly, the application is intended to cover alternatives, modifications and equivalents, which may be included within the spirit and scope of the MEMS resonator disclosed herein.

[0074] Reference Signs List

[0075] 100, 200, 300, 400: Overtone Resonators

[0076] 100A, 100B, 100C, 100D: Resonator Plates

[0077] 200A, 200B, 200C, 200D: Resonator Plates

[0078] 300A, 300B, 300C, 300D: Resonator Plates

[0079] 400A, 400B, 400C, 400D: Resonator Plates

[0080] 102A, 104A, 102B, 104B, 102C, 104C, 102D, 104D: Long sides of resonator plates

[0081] 106A, 108A, 106B, 108B, 106C, 106D, 108C, 108D: Short sides of resonator plates

[0082] 110, 111, 112, 112: Anchoring points

[0083] 202A, 204A, 202B, 204B, 202C, 204C, 202D, 204D: Long sides of resonator plates

[0084] 206A, 208A, 206B, 208B, 206C, 206D, 208C, 208D: Short sides of resonator plates

[0085] 401A, 402A, 403A, 404A, 401D, 402D, 403D, 404D: short side portions of resonator plates

CLAIMS

What is claimed:

1. A microelectromechanical system ("MEMS") resonator comprising:

a plurality of first resonator plates each having a width $W1$ and a length $L1$, wherein the length $L1 >$ the width $W1$; and

a plurality of second resonator plates each having a width $W2$ and a length $L2$, wherein the length $L2 >$ the width $W2$,

wherein the plurality of first resonator plates and the plurality of second resonator plates are disposed parallel to each other in a widthwise direction of the MEMS resonator, and

wherein the length $L1$ is not equal to the length $L2$.

2. The MEMS resonator according to claim 1, wherein the plurality of second resonator plates comprise at least a pair of second resonator plates that are respectively disposed adjacent to outer sides in the widthwise direction of at least a pair of the plurality of first resonator plates.

3. The MEMS resonator according to claim 2, wherein the pair of first resonator plates are disposed adjacent to each other at respective inner sides in the widthwise direction of the first

resonator plates, the inner sides being opposite to the outer sides.

4. The MEMS resonator according to claim 2, wherein the MEMS resonator comprises a symmetric shape such that the plurality of second resonator plates are aligned symmetrically relative to the plurality of first resonator plates in the widthwise direction.

5. The MEMS resonator according to claim 2, wherein the length L_2 of each of the second resonator plates is substantially equal to $0.98 \times$ the length L_1 of the first resonator plates.

6. The MEMS resonator according to claim 1, wherein the length L_2 of each of the second resonator plates is substantially equal to $0.98 \times$ the length L_1 of the first resonator plates.

7. The MEMS resonator according to claim 5, wherein the width W_1 of each of the first resonator plates is substantially equal to the width W_2 of each of the second resonator plates.

8. The MEMS resonator according to claim 2, further comprising at least one third resonator plate having a length L_3 that is not equal to the length L_1 or the length L_2 .

9. The MEMS resonator according to claim 8, wherein the lengths L1, L2 and L3 of the respective resonator plates satisfy the following:

$$0.001 < \left| \frac{L_i}{L_{i+1}} - 1 \right| < 0.1,$$

wherein i and $i+1$ are any two adjacent resonator plates of the MEMS resonator, and

wherein L_i and L_{i+1} are average lengths of at least a pair of adjacent resonator plates in the widthwise direction.

10. The MEMS resonator according to claim 1, wherein the length L1 of each of the first resonator plates and the length L2 of each of the second resonator plates satisfies the following:

$$0.001 < \left| \frac{L1}{L2} - 1 \right| < 0.1.$$

11. The MEMS resonator according to claim 10, wherein the width W1 of each of the first resonator plates and the width W2 of each of the second resonator plates satisfies the following:

$$\left| \frac{W1}{W2} - 1 \right| < 0.1.$$

12. The MEMS resonator according to claim 11, wherein the length L1 of each of the first resonator plates and the length L2 of each of the second resonator plates satisfies the following:

$$0.002 < \left| \frac{L_1}{L_2} - 1 \right| < 0.05.$$

13. A microelectromechanical system ("MEMS") resonator comprising:

a plurality of inner resonator plates each having a width W1 and a length L1 that is greater than the width W1, wherein the inner resonator plates are disposed adjacent to each other along respective first sides of the inner resonator plates; and

a plurality of outer resonator plates each having a width W2 and a length L2 that is greater than the width W2, wherein at least a pair of the outer resonator plates are disposed adjacent to respective second sides of a pair of the inner resonator plates,

wherein the second sides of the pair of inner resonator plates are opposite the first sides, respectively, in the widthwise direction of the MEMS resonator, and

wherein the length L1 is not equal to the length L2.

14. The MEMS resonator according to claim 13, wherein the length L2 of each of the outer resonator plates is substantially equal to 0.98 x the length L1 of the inner resonator plates.

15. The MEMS resonator according to claim 13, wherein the length L1 of each of the inner resonator plates and the length

L2 of each of the outer resonator plates satisfies the following:

$$0.001 < \left| \frac{L1}{L2} - 1 \right| < 0.1.$$

16. A microelectromechanical system ("MEMS") resonator comprising:

a plurality of first resonator plates each being rectangular shaped and having a pair of longer sides with a length L1 and a pair of shorter sides with a width W1, wherein the length L1 > the width W1; and

a plurality of second resonator plates each having a pair of first sides extending in a direction parallel to each other and a pair of second sides connecting the pair of first sides, respectively, the pair of second sides not extending in a direction parallel to each other,

wherein the plurality of first resonator plates and the plurality of second resonator plates are disposed parallel to each other in a widthwise direction of the MEMS resonator.

17. The MEMS resonator according to claim 16, wherein the plurality of second resonator plates are trapezoid shaped, wherein each of the second resonator plates includes one side of

the pair of first sides having a length $L1$ and the other side of the pair of first sides having a length $L2 < \text{the length } L1$.

18. The MEMS resonator according to claim 17, wherein the plurality of second resonator plates comprise at least a pair of second resonator plates that are respectively disposed adjacent to outer sides in the widthwise direction of a pair of the plurality of first resonator plates.

19. The MEMS resonator according to claim 17, wherein the plurality of second resonator plates each comprise an average length that is substantially equal to $L2a = (L1+L2)/2$, and wherein the average length satisfies the following:

$$0.001 < \left| \frac{L1}{L2a} - 1 \right| < 0.1.$$

20. The MEMS resonator according to claim 16, wherein the each side of the pair of second sides of the second resonator plates is concave shaped.



Fig. 1A
(Prior Art)

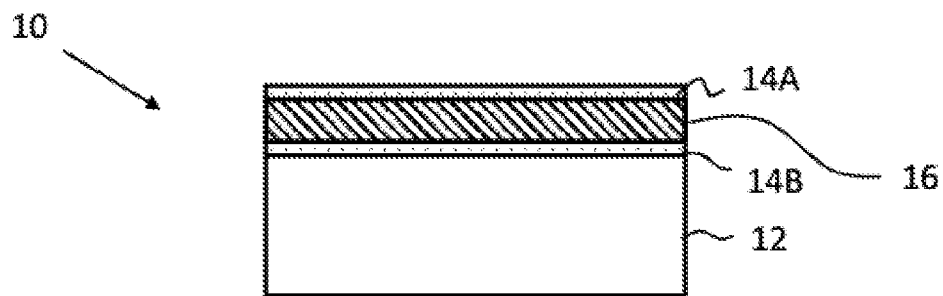


Fig. 1B
(Prior Art)

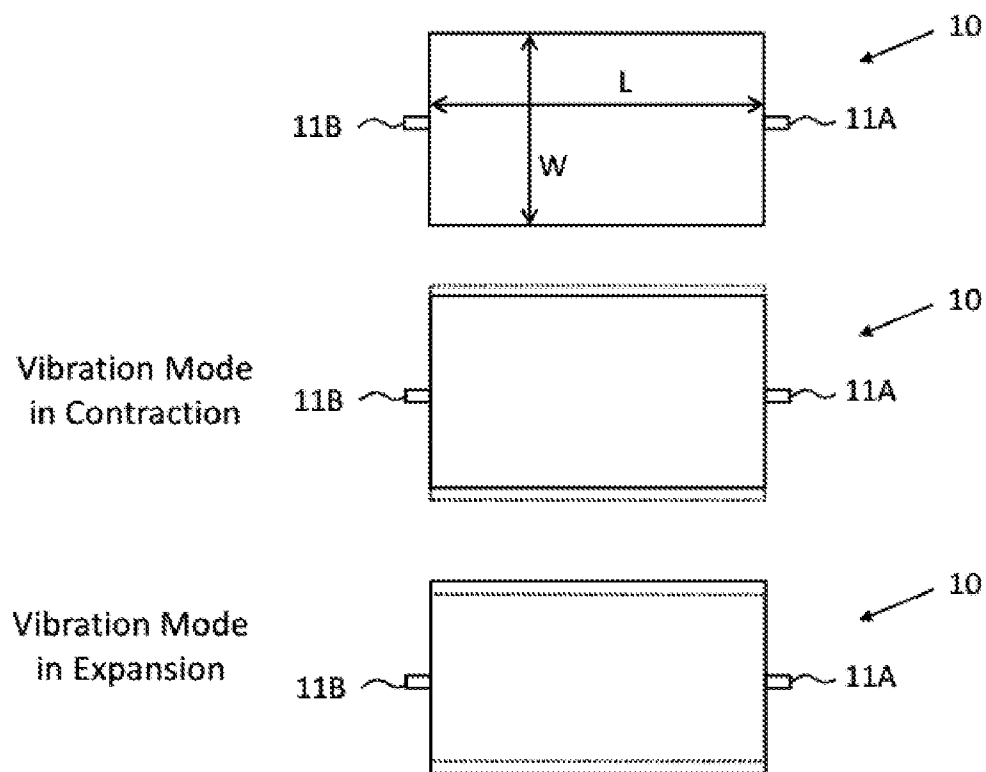


Fig. 2
(Prior Art)

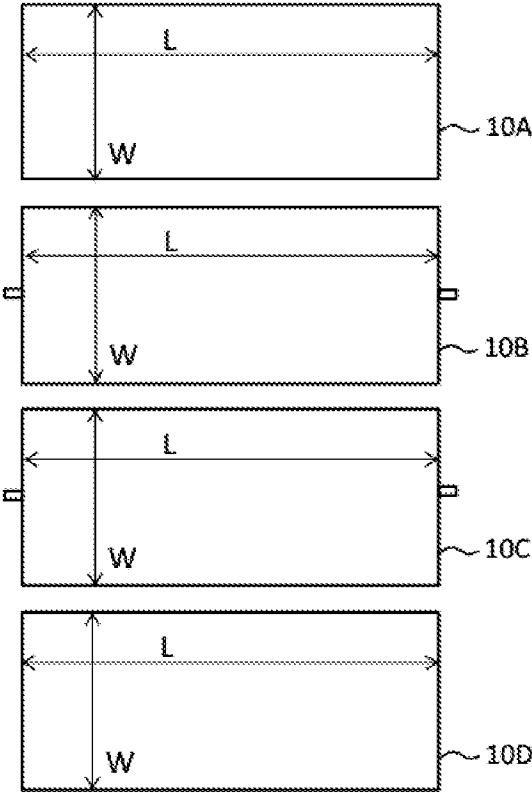


Fig. 3A
(Prior Art)

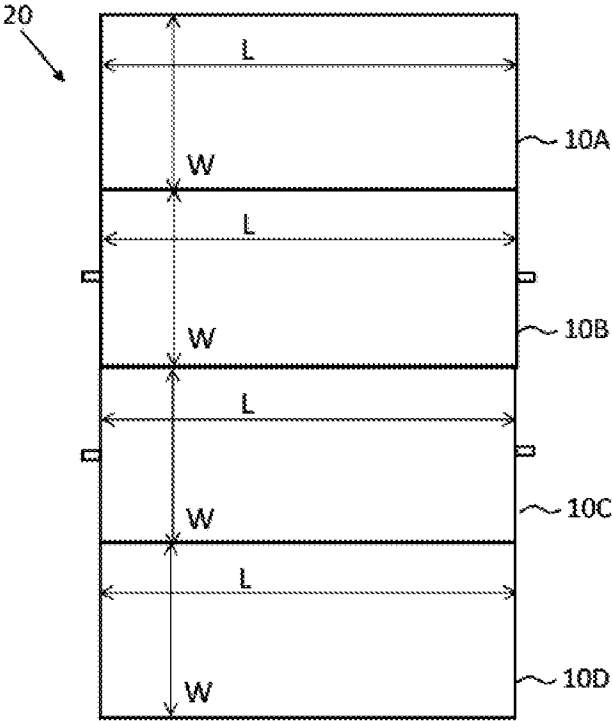


Fig. 3B
(Prior Art)

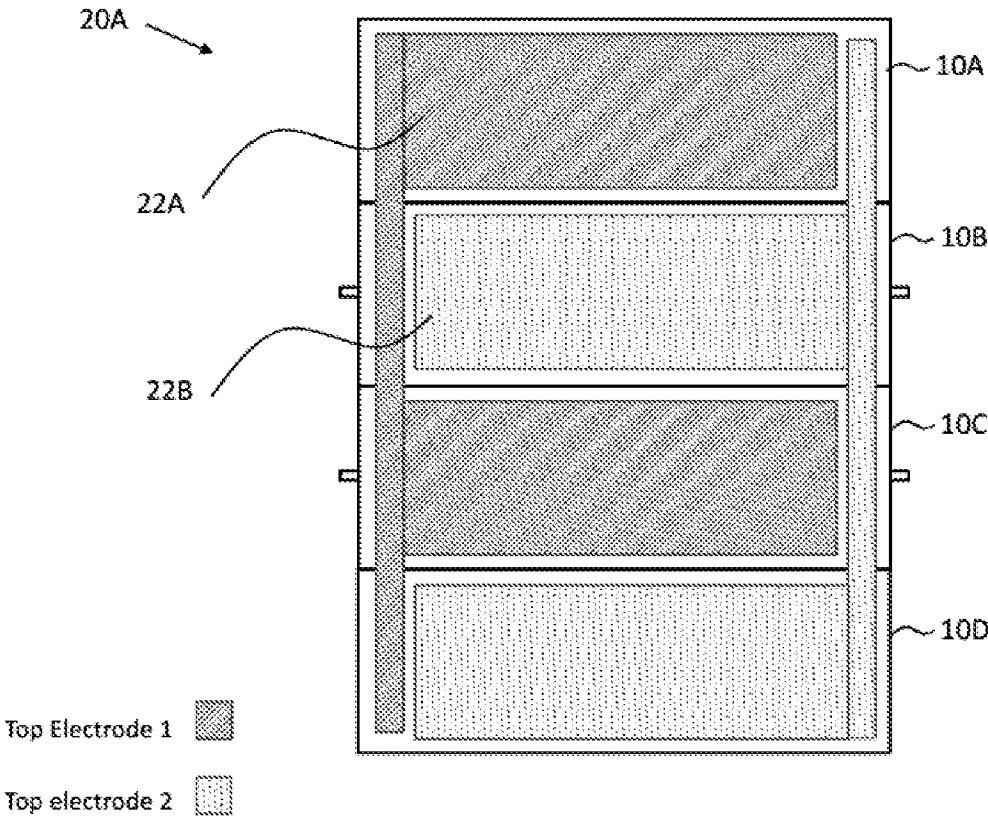


Fig. 3C
(Prior Art)

Fig. 4A

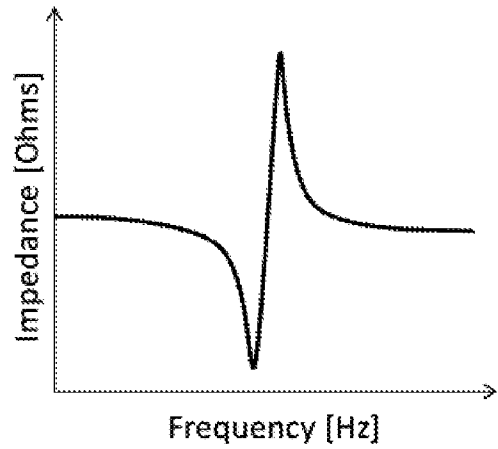
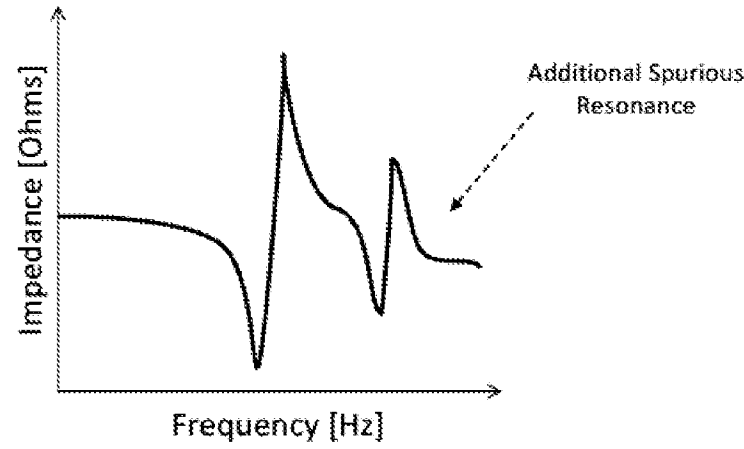
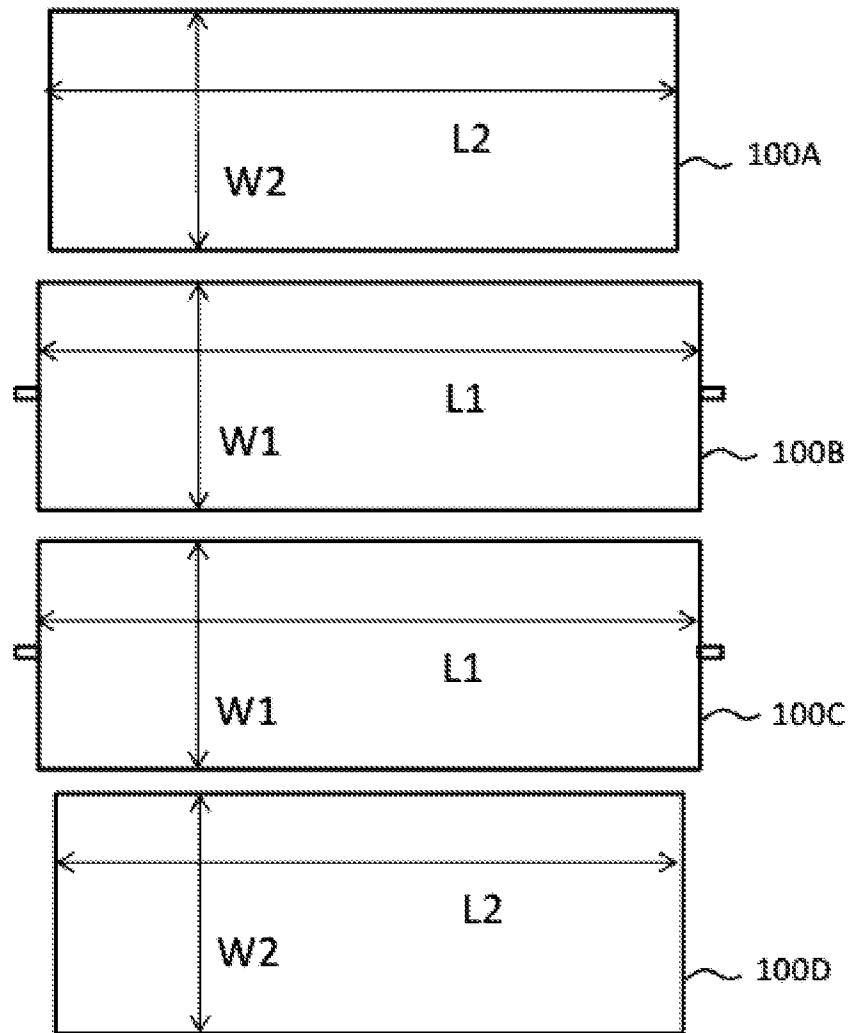


Fig. 4B



**Fig. 5A**

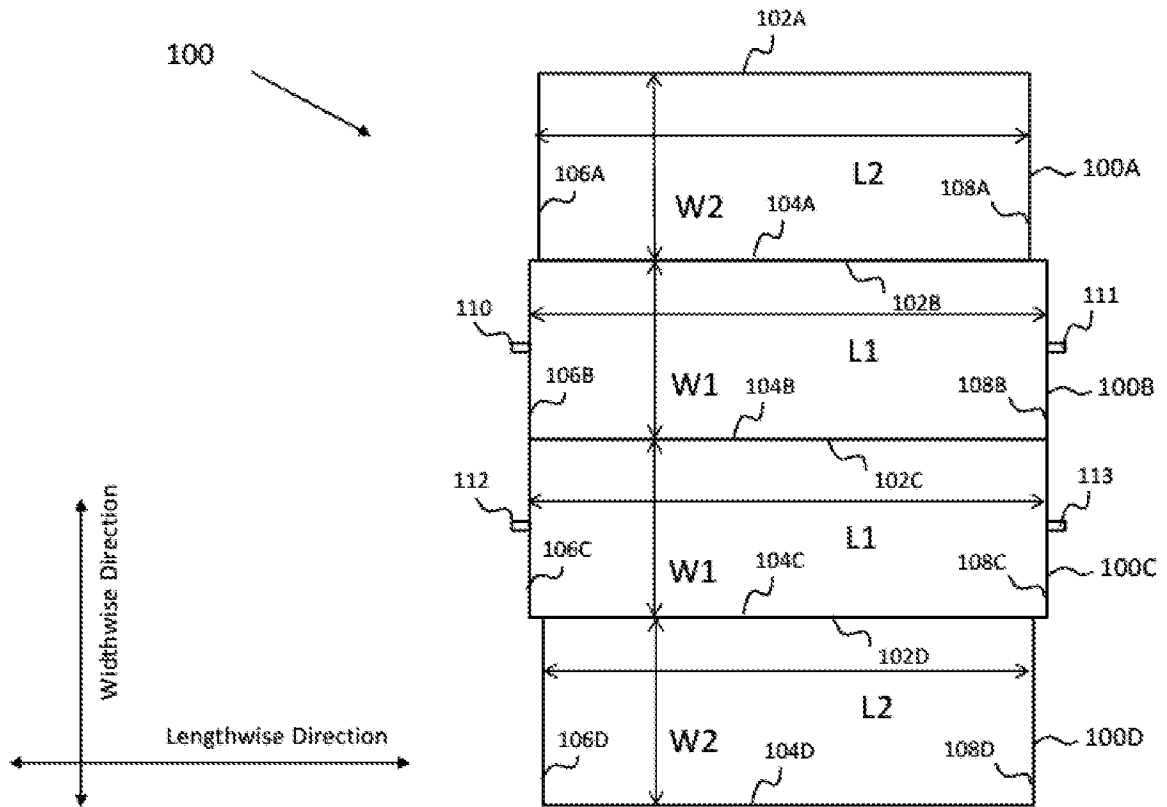


Fig. 5B

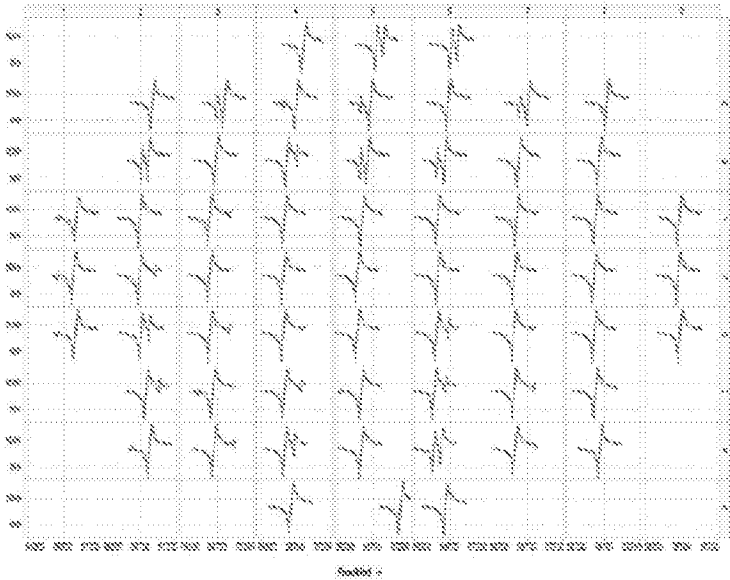


Fig. 5C
(Prior Art)

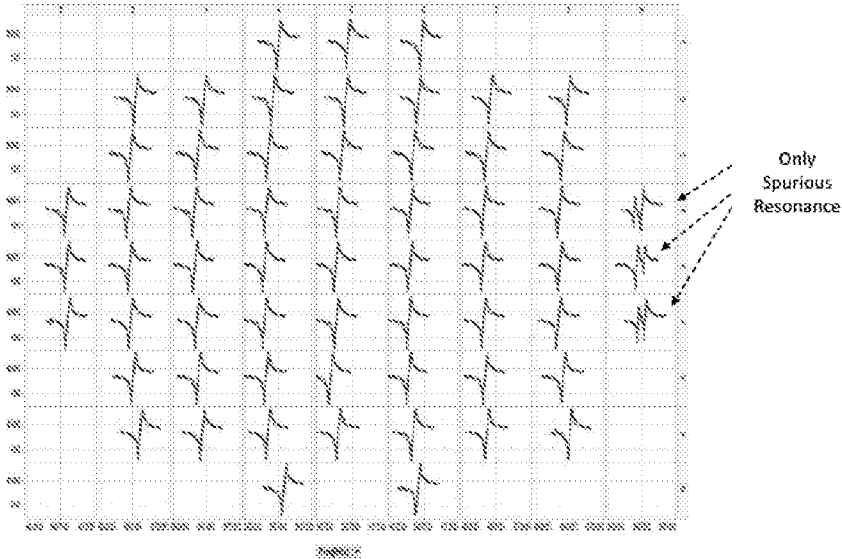


Fig. 5D

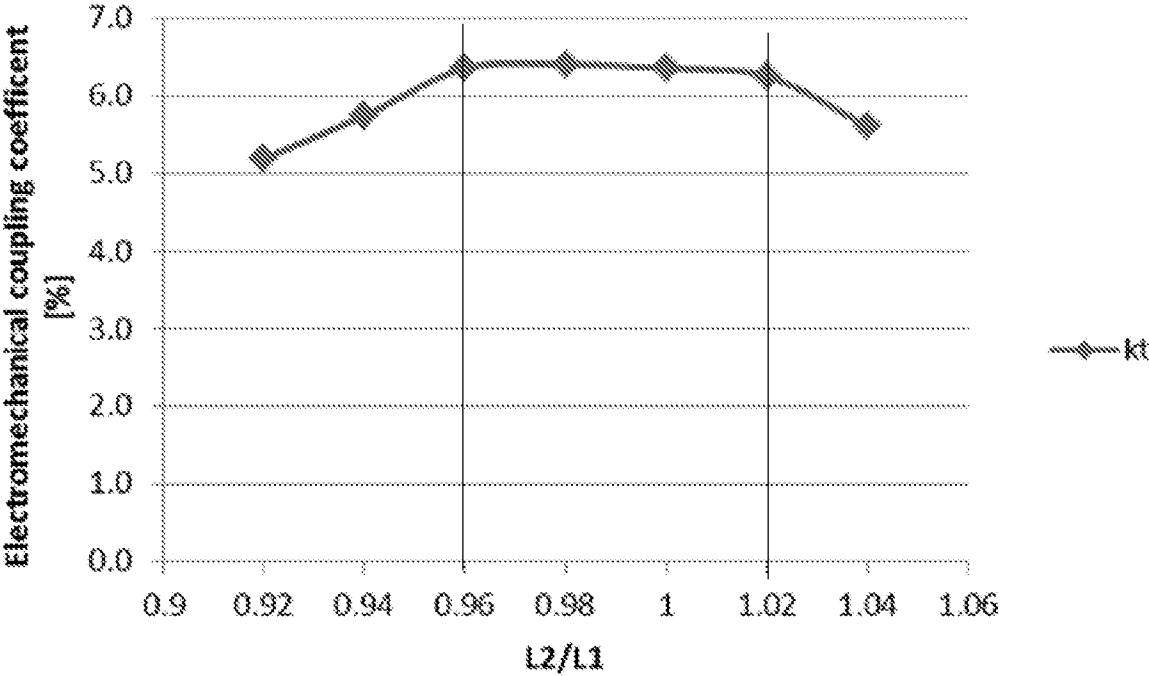


Fig. 5E

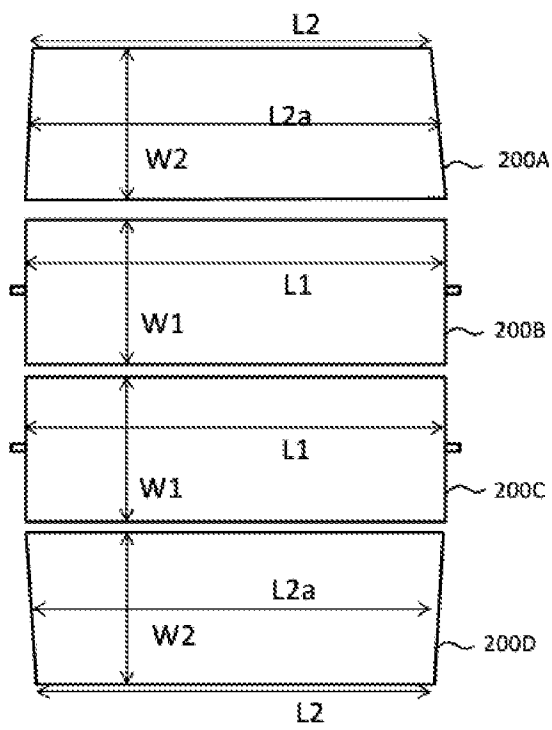


Fig. 6A

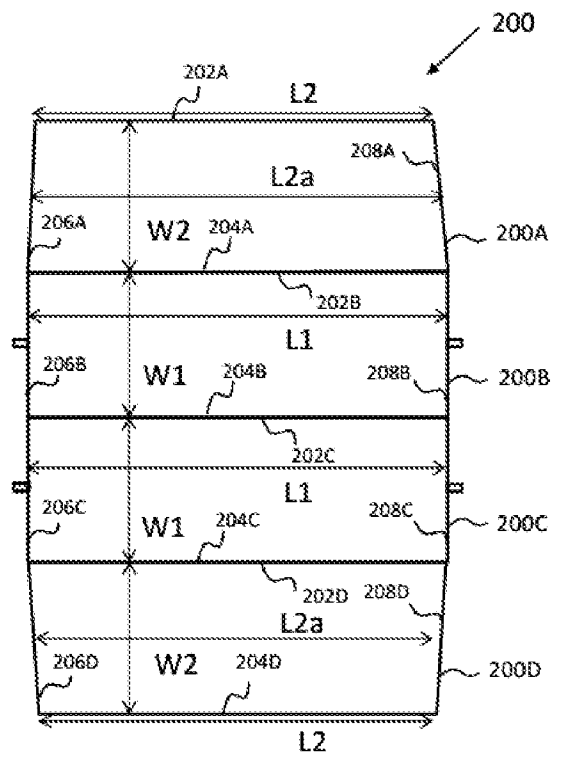


Fig. 6B

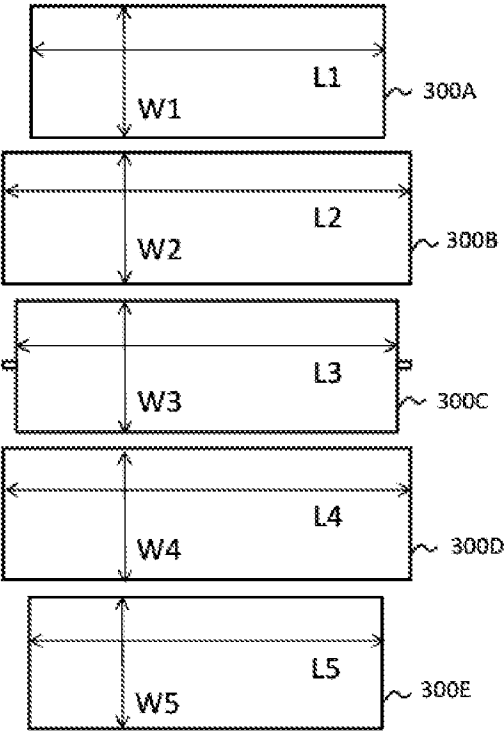


Fig. 7A

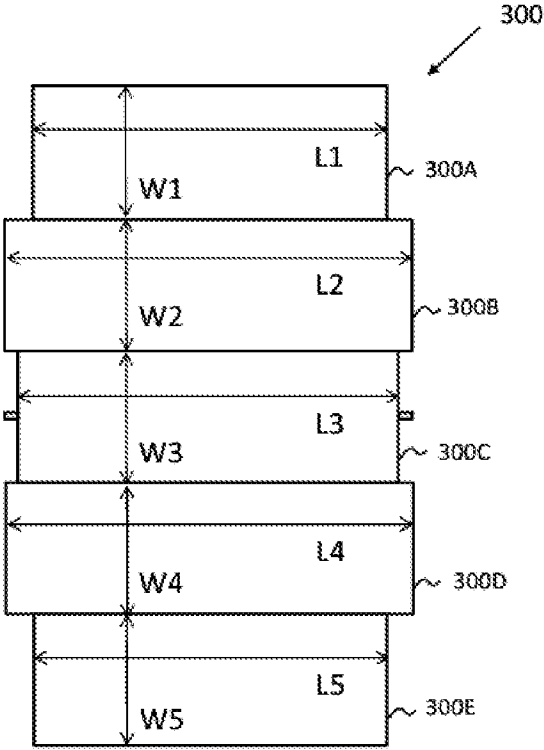


Fig. 7B

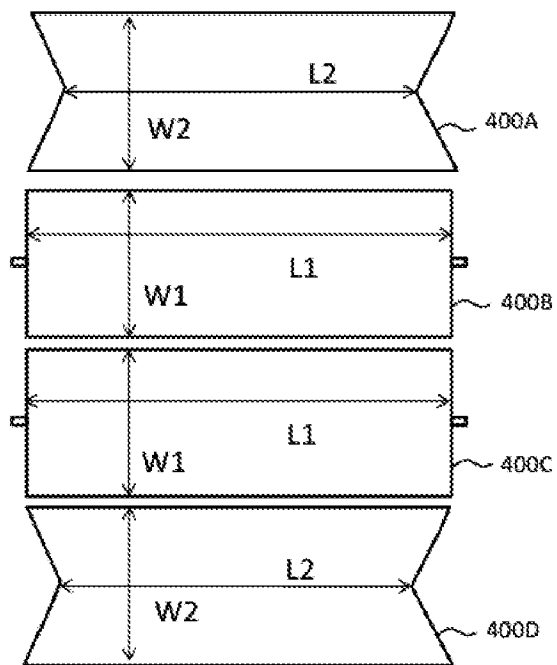


Fig. 8A

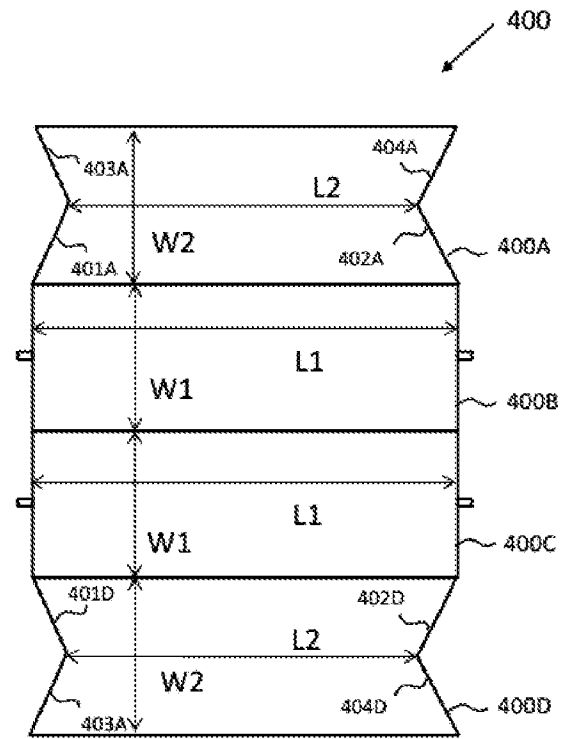


Fig. 8B

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2017/058763

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - H03H 9/02; H03H 9/00; H03H 9/15; H03H 9/24 (2018.01)

CPC - H03H 9/02244; H03H 9/02433; H03H 9/205; H03H 9/2405 (2017.08)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

See Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

USPC - 310/311; 310/328; 333/186; 333/197 (keyword delimited)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

See Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 9,318,998 B1 (GEORGIA TECH RESEARCH CORPORATION) 19 April 2016 (19.04.2016)	1-15
---	entire document	---
Y		16-20
Y	US 2010/0109810 A1 (HASHIMURA) 06 May 2010 (06.05.2010) entire document	16-20
A	US 6,940,370 B2 (BIRCUMSHAW et al) 06 September 2005 (06.09.2005) entire document	1-20

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

15 December 2017

Date of mailing of the international search report

12 JAN 2018

Name and mailing address of the ISA/US

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