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(54) **Title:** ACOUSTICALLY DECOUPLED MEMS DEVICES

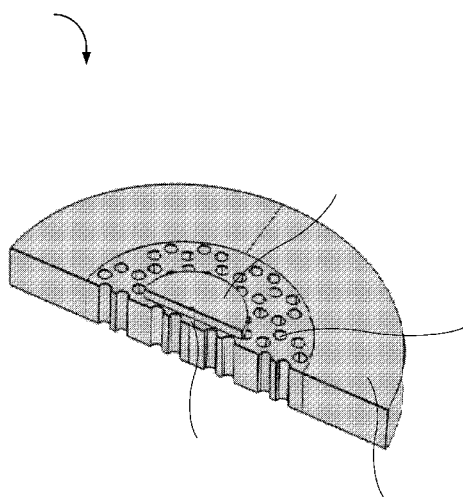


FIG. 1

(57) **Abstract:** Embodiments of the present disclosure relate generally to acoustically decoupled microelectromechanical system devices and, more particularly, to acoustically decoupled microelectromechanical system devices anchored upon phononic crystals. In some embodiments described herein, a device may comprise a resonator, a handle layer, and a pedestal disposed between the resonator and the handle layer, the pedestal connecting the resonator to the handle layer. In the devices described herein, the resonator and the handle layer may be non-coplanar. In some embodiments, the handle layer comprises a phononic crystal to acoustically decouple the resonator from the substrate of the handle layer.



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ACOUSTICALLY DECOUPLED MEMS DEVICES**CROSS-REFERENCE TO RELATED APPLICATIONS**

[0001] This Application claims priority to U.S. Provisional Patent Application No. 62/638,494, filed 5 March 2018, which is hereby incorporated by reference herein in its entirety as if fully set forth below.

STATEMENT OF RIGHTS UNDER FEDERALLY SPONSORED RESEARCH

[0002] This invention was made with Government support under Agreement No. N66001-16-1-4027 awarded by DARPA. The Government has certain rights in the invention.

FIELD OF THE DISCLOSURE

[0003] Embodiments of the present disclosure relate generally to acoustically decoupled microelectromechanical system devices and, more particularly, to acoustically decoupled microelectromechanical system devices anchored upon phononic crystals.

BACKGROUND

[0004] The pursuit of ultra-high quality factors in micro- and nano-microelectromechanical system (“MEMS”) devices is of great interest and importance, benefiting a wide range of applications. In this pursuit, acoustically decoupling the MEMS device (e.g., accelerometer, pressure sensor, gyroscope, clocks, etc.) from the substrate is often key. When coupled, time-varying stress in the substrate can negatively impact the MEMS device performance, by inducing drift for example. Previous systems for acoustically decoupling MEMS devices focused on defining coplanar mesas around the device. The collection of these mesas, when arranged symmetrically with a definable unit-cell, form a phononic crystal. In well-designed phononic crystals, acoustic waves of a certain frequency scatter destructively and cannot propagate energy between the MEMS device and the substrate. These previous, coplanar systems, however, suffer from other mechanisms that degrade the performance of the systems.

[0005] The coplanar design of current acoustic-decoupling systems requires a large footprint for the MEMS device. A resonator, for example, in the center of the mesas of the phononic crystal requires sufficient area around the resonator to incorporate the unit-cells of the phononic crystal. This large footprint is only exacerbated if additional circuitry is added to the device, for example electrodes and circuitry for electrodes. Also, placing the resonator and phononic crystal in the same plane inherently requires both features to be manufactured from the same material and with similar dimensions (i.e., thickness). Therefore, with current systems, the characteristics of the MEMS device and the phononic crystal cannot be

independently manipulated to improve the characteristics for each component of the system, for example phonon-phonon dissipation for the MEMS device and acoustic dissipation for the phononic crystal. What is needed, therefore, is a system providing an acoustically-decoupled MEMS device that maintains a small footprint, while also providing customizability for the independent components of the device.

SUMMARY

[0006] Embodiments of the present disclosure address these concerns as well as other needs that will become apparent upon reading the description below in conjunction with the drawings. Briefly described, embodiments of the present disclosure relate generally to acoustically decoupled microelectromechanical system devices and, more particularly, to acoustically decoupled microelectromechanical system devices anchored upon phononic crystals.

[0007] An exemplary embodiment of the present invention provides a device. The device may comprise a resonator comprising a perimeter edge. The device may further comprise a handle layer comprising a phononic crystal structure. The device may further comprise a pedestal. The pedestal may be disposed between the resonator and the handle layer. The pedestal may connect the resonator to the handle layer. The device may further comprise a gap disposed between the resonator and the handle layer.

[0008] In any of the embodiments described herein, the resonator and the handle layer be non-coplanar.

[0009] In any of the embodiments described herein, the handle layer may comprise a first side and a second side. The first side may be proximate the pedestal. A handle layer thickness may be disposed between the first side and the second side. The handle layer thickness may be approximately $\lambda/4$, where λ is equal to a wavelength of an acoustic wave propagating through the handle layer corresponding to a resonator frequency.

[0010] In any of the embodiments described herein, the handle layer may comprise a plurality of structures etched into the handle layer.

[0011] In any of the embodiments described herein, the handle layer may comprise a lattice structure having a plurality of unit-cells.

[0012] In any of the embodiments described herein, the lattice structure may comprise at least three unit-cells.

[0013] In any of the embodiments described herein, the lattice structure may be a honeycomb lattice structure. A honeycomb lattice structure may have a unit-cell length of from between 10 μ m and 1500 μ m.

- [0014] In any of the embodiments described herein, the resonator may be a gyroscope.
- [0015] In any of the embodiments described herein, the perimeter edge of the resonator may be circular.
- [0016] In any of the embodiments described herein, the perimeter edge of the resonator may be square or rectangular.
- [0017] In any of the embodiments described herein, the resonator may comprise a diameter of from between 100 μ m and 5mm.
- [0018] In any of the embodiments described herein, the resonator may comprise a first diameter. The pedestal may comprise a second diameter. The second diameter may be from between 1% and 10% of the first diameter.
- [0019] In any of the embodiments described herein, the resonator may comprise a width and/or length of from between 100 μ m and 5mm.
- [0020] In any of the embodiments described herein, the pedestal may comprise a first end and a second end, wherein the first end is proximate the resonator, and wherein the second end is proximate the handle layer. The pedestal may comprise a length disposed between the first end and the second end. The length may be from between 1 μ m to 500 μ m.
- [0021] In any of the embodiments described herein, the pedestal may comprise at least one of a conical frustum or a cylindrical shape.
- [0022] In any of the embodiments described herein, the resonator may comprise at least one of silicon carbide, aluminum nitride, polycrystalline silicon carbide, polycrystalline silicon, diamond, or fused quartz.
- [0023] In any of the embodiments described herein, the resonator may comprise a first material composition, and the handle layer may comprise a second material composition. In any of the embodiments described herein, the first material composition may be different than the second material composition.
- [0024] In any of the embodiments described herein, the device may further comprise an electrode connected to the handle layer. The electrode may be disposed proximate the perimeter edge of the resonator. The device may further comprise a capacitive gap disposed between the electrode and the resonator.
- [0025] In any of the embodiments described herein, the capacitive gap may be from between 100nm and 500nm.
- [0026] In any of the embodiments described herein, the electrode may be connected to the handle layer by an electrode pedestal.

[0027] In any of the embodiments described herein, the resonator may have a quality factor greater than 2,000,000.

[0028] Another exemplary embodiment of the present invention provides a MEMS device. The device may comprise a resonator gyroscope comprising a perimeter edge. The device may further comprise a handle layer comprising a phononic crystal structure. The device may further comprise a pedestal. The pedestal may be disposed between the resonator gyroscope and the handle layer. The pedestal may connect the resonator gyroscope to the handle layer. The device may further comprise a gap disposed between the resonator gyroscope and the handle layer.

[0029] In any of the embodiments described herein, the resonator gyroscope and the handle layer be non-coplanar.

[0030] In any of the embodiments described herein, the handle layer may comprise a first side and a second side. The first side may be proximate the pedestal. A handle layer thickness may be disposed between the first side and the second side. The handle layer thickness may be approximately $\lambda/4$, where λ is equal to a wavelength of an acoustic wave propagating through the handle layer corresponding to a resonator gyroscope frequency.

[0031] In any of the embodiments described herein, the handle layer may comprise a plurality of structures etched into the handle layer.

[0032] In any of the embodiments described herein, the handle layer may comprise a lattice structure having a plurality of unit-cells.

[0033] In any of the embodiments described herein, the lattice structure may comprise at least three unit-cells.

[0034] In any of the embodiments described herein, the lattice structure may be a honeycomb lattice structure. A honeycomb lattice structure may have a unit-cell length of from between 10 μ m and 1500 μ m.

[0035] In any of the embodiments described herein, the perimeter edge of the resonator gyroscope may be circular.

[0036] In any of the embodiments described herein, the resonator gyroscope may comprise a diameter of from between 100 μ m and 5mm.

[0037] In any of the embodiments described herein, the resonator gyroscope may comprise a first diameter. The pedestal may comprise a second diameter. The second diameter may be from between 1% and 10% of the first diameter.

[0038] In any of the embodiments described herein, the handle layer may be cylindrical. The resonator gyroscope may comprise a first diameter, and the handle layer may comprise a second diameter. The second diameter may be greater than the first diameter.

[0039] In any of the embodiments described herein, the perimeter edge of the resonator gyroscope may be square or rectangular.

[0040] In any of the embodiments described herein, the resonator may comprise a width and/or length of from 100 μ m and 5mm.

[0041] In any of the embodiments described herein, the pedestal may comprise a first end and a second end, wherein the first end is proximate the resonator gyroscope, and wherein the second end is proximate the handle layer. The pedestal may comprise a length disposed between the first end and the second end. The length may be from between 1 μ m to 500 μ m.

[0042] In any of the embodiments described herein, the pedestal may comprise at least one of a conical frustum or a cylindrical shape.

[0043] In any of the embodiments described herein, the resonator gyroscope may comprise at least one of silicon carbide, aluminum nitride, polycrystalline silicon carbide, polycrystalline silicon, diamond, or fused quartz.

[0044] In any of the embodiments described herein, the device may further comprise an electrode connected to the handle layer. The electrode may be disposed proximate the perimeter edge of the resonator gyroscope. The device may further comprise a capacitive gap disposed between the electrode and the resonator gyroscope.

[0045] In any of the embodiments described herein, the capacitive gap may be from between 100nm and 500nm.

[0046] Another exemplary embodiment of the present invention provides a MEMS gyroscope. The MEMS gyroscope may comprise a disk resonator having a perimeter edge. The perimeter edge may have a first diameter. The MEMS gyroscope may further comprise a handle layer comprising a phononic crystal structure. The handle layer may comprise a thickness of approximately $\lambda/4$, wherein λ is equal to a wavelength of an acoustic wave propagating through the handle layer corresponding to a disk resonator frequency. The MEMS gyroscope may further comprise a pedestal disposed between the disk resonator and the handle layer. The pedestal may connect the disk resonator to the handle layer. The pedestal may comprise a second diameter. The second diameter may be less than the first diameter.

[0047] In any of the embodiments described herein, the handle layer may comprise a plurality of structures etched into the handle layer.

[0048] In any of the embodiments described herein, the handle layer may comprise a lattice structure having a plurality of unit-cells.

[0049] In any of the embodiments described herein, the lattice structure may be a honeycomb lattice structure. The honeycomb lattice structure may have a unit-cell length of from between 10 μ m and 1500 μ m.

[0050] In any of the embodiments described herein, the disk resonator may comprise at least one of silicon carbide, aluminum nitride, polycrystalline silicon carbide, polycrystalline silicon, diamond, or fused quartz.

[0051] In any of the embodiments described herein, the MEMS gyroscope may further comprise a plurality of electrodes disposed proximate the perimeter edge of the disk resonator. The MEMS gyroscope may further comprise a capacitive gap disposed between the disk resonator and each electrode of the plurality of electrodes.

[0052] In any of the embodiments described herein, the capacitive gap may be from between 100nm and 500nm.

[0053] In any of the embodiments described herein, at least part of the plurality of electrodes may be configured to actuate the disk resonator.

[0054] In any of the embodiments described herein, the disk resonator may have a quality factor greater than 2,000,000.

[0055] Another exemplary embodiment of the present invention provides a MEMS gyroscope. The MEMS gyroscope may comprise a disk resonator gyroscope comprising a perimeter edge and having a first diameter. The MEMS gyroscope may further comprise a handle layer comprising a phononic crystal structure. The handle layer may comprise a thickness of approximately $\lambda/4$, wherein λ is equal to a wavelength of an acoustic wave propagating through the handle layer corresponding to a disk resonator gyroscope frequency. The MEMS gyroscope may further comprise a pedestal disposed between the disk resonator and the handle layer. The pedestal may connect the disk resonator gyroscope to the handle layer. The pedestal may comprise a second diameter. The second diameter may be less than the first diameter. The MEMS gyroscope may further comprise a plurality of electrodes disposed proximate the perimeter edge of the disk resonator gyroscope. The MEMS gyroscope may further comprise a capacitive gap disposed between the disk resonator gyroscope and each of the plurality of electrodes.

[0056] In any of the embodiments described herein, the capacitive gap may be from between 100nm and 10 μ m.

[0057] In any of the embodiments described herein, the capacitive gap may be from between 100nm and 500nm.

[0058] In any of the embodiments described herein, at least part of the plurality of electrodes may be sense electrodes.

[0059] In any of the embodiments described herein, the plurality of electrodes may be connected to the handle layer by an electrode pedestal.

[0060] In any of the embodiments described herein, the handle layer may comprise a plurality of structures etched into the handle layer.

[0061] In any of the embodiments described herein, the handle layer may comprise a lattice structure having a plurality of unit-cells.

[0062] In any of the embodiments described herein, the lattice structure may be a honeycomb lattice structure. The honeycomb lattice structure may have a unit-cell length of from between 10 μ m and 1500 μ m.

[0063] In any of the embodiments described herein, the disk resonator gyroscope may comprise at least one of silicon carbide, aluminum nitride, polycrystalline silicon carbide, polycrystalline silicon, diamond, or fused quartz.

[0064] In any of the embodiments described herein, the disk resonator gyroscope may have a quality factor greater than 2,000,000.

[0065] These and other aspects of the present disclosure are described in the Detailed Description below and the accompanying figures. Other aspects and features of embodiments of the present disclosure will become apparent to those of ordinary skill in the art upon reviewing the following description of specific, example embodiments of the present disclosure in concert with the figures. While features of the present disclosure may be discussed relative to certain embodiments and figures, all embodiments of the present disclosure can include one or more of the features discussed herein. Further, while one or more embodiments may be discussed as having certain advantageous features, one or more of such features may also be used with the various embodiments of the disclosure discussed herein. In similar fashion, while example embodiments may be discussed below as device, system, or method embodiments, it is to be understood that such example embodiments can be implemented in various devices, systems, and methods of the present disclosure.

BRIEF DESCRIPTION OF THE FIGURES

[0066] Reference will now be made to the accompanying figures and diagrams, which are not necessarily drawn to scale, and wherein:

[0067] **FIG. 1** is a cross-sectional view of an acoustically decoupled device comprising a resonator anchored upon a handle layer, according to an exemplary embodiment of the present disclosure.

[0068] **FIG. 2** is a perspective view of an acoustically decoupled device comprising a resonator anchored upon a handle layer, according to an exemplary embodiment of the present disclosure.

[0069] **FIG. 3** is a side perspective view of an acoustically decoupled device comprising a resonator anchored upon a handle layer by a pedestal, according to an exemplary embodiment of the present disclosure.

[0070] **FIG. 4A** depicts an exemplary honeycomb lattice structure with inclusions.

[0071] **FIG. 4B** depicts an exemplary unit-cell length α for a honeycomb lattice.

[0072] **FIG. 5** is a graph showing an exemplary bandgap for a honeycomb lattice structure.

[0073] **FIG. 6A** depicts an exemplary square lattice structure with inclusions.

[0074] **FIG. 6B** depicts an exemplary unit-cell length α for a square lattice.

[0075] **FIG. 7** is a graph showing an exemplary bandgap for a square lattice structure.

[0076] **FIG. 8** is a graph showing the relationship of handle layer thickness to Q_{ANC} .

[0077] **FIG. 9** is a graph showing the relationship between unit-cell quantity and quality factor Q .

[0078] **FIG. 10A** a perspective view of a MEMS device comprising a resonator and a plurality of electrodes, according to an exemplary embodiment of the present disclosure.

[0079] **FIG. 10B** is a cross-sectional view of an acoustically decoupled device with a resonator connected to a handle layer by a pedestal, wherein the device further comprises electrodes, according to an exemplary embodiment of the present disclosure.

[0080] **FIG. 11** is a graph presenting the results of testing an exemplary disk resonator anchored upon a handle layer comprising a phononic crystal.

[0081] **FIG. 12** is a graph showing the relationship between striation radius for the resonator and Q_{TED} .

[0082] **FIG. 13** is an atomic force micrograph of the sidewall of an exemplary disk resonator anchored upon a handle layer comprising a phononic crystal.

DETAILED DESCRIPTION

[0083] Although certain embodiments of the disclosure are explained in detail, it is to be understood that other embodiments are contemplated. Accordingly, it is not intended that the disclosure is limited in its scope to the details of construction and arrangement of components

set forth in the following description or illustrated in the drawings. Other embodiments of the disclosure are capable of being practiced or carried out in various ways. Also, in describing the embodiments, specific terminology will be resorted to for the sake of clarity. It is intended that each term contemplates its broadest meaning as understood by those skilled in the art and includes all technical equivalents which operate in a similar manner to accomplish a similar purpose.

[0084] It should also be noted that, as used in the specification and the appended claims, the singular forms “a,” “an” and “the” include plural references unless the context clearly dictates otherwise. References to a composition containing “a” constituent is intended to include other constituents in addition to the one named.

[0085] Ranges may be expressed herein as from “about” or “approximately” or “substantially” one particular value and/or to “about” or “approximately” or “substantially” another particular value. When such a range is expressed, other exemplary embodiments include from the one particular value and/or to the other particular value.

[0086] Herein, the use of terms such as “having,” “has,” “including,” or “includes” are open-ended and are intended to have the same meaning as terms such as “comprising” or “comprises” and not preclude the presence of other structure, material, or acts. Similarly, though the use of terms such as “can” or “may” are intended to be open-ended and to reflect that structure, material, or acts are not necessary, the failure to use such terms is not intended to reflect that structure, material, or acts are essential. To the extent that structure, material, or acts are presently considered to be essential, they are identified as such.

[0087] It is also to be understood that the mention of one or more method steps does not preclude the presence of additional method steps or intervening method steps between those steps expressly identified. Moreover, although the term “step” may be used herein to connote different aspects of methods employed, the term should not be interpreted as implying any particular order among or between various steps herein disclosed unless and except when the order of individual steps is explicitly required.

[0088] The components described hereinafter as making up various elements of the disclosure are intended to be illustrative and not restrictive. Many suitable components that would perform the same or similar functions as the components described herein are intended to be embraced within the scope of the disclosure. Such other components not described herein can include, but are not limited to, for example, similar components that are developed after development of the presently disclosed subject matter. Additionally, the components described herein may apply to any other component within the disclosure. Merely discussing

a feature or component in relation to one embodiment does not preclude the feature or component from being used or associated with another embodiment.

[0089] To facilitate an understanding of the principles and features of the disclosure, various illustrative embodiments are explained below. In particular, the presently disclosed subject matter is described in the context of acoustically-decoupled resonators and gyroscopes anchored upon phononic crystals. The present disclosure, however, is not so limited and can be applicable in other contexts. For example, and not limitation, some embodiments of the present disclosure may improve the functionality of other electromechanical systems, including but not limited to accelerometers and oscillators. Additionally, although certain materials are described within the present disclosure, the description of those materials is merely exemplary, and other materials for MEMS devices may be used with the presently described systems and methods, as will be appreciated by those having skill in the art. These embodiments are contemplated within the scope of the present disclosure. Accordingly, when the present disclosure is described in the context of acoustically-decoupled resonators and gyroscopes anchored upon phononic crystals, it will be understood that other embodiments can take the place of those referred to.

[0090] As described above, the pursuit of ultra-high quality factors (Q) in micro- and nano-scale MEMS devices is of great interest and importance, benefiting a wide range of applications. Bulk acoustic wave (BAW) disk resonator gyroscopes offer a host of benefits including shock and vibration resilience, high bandwidth and high Q in moderate vacuum environment, thanks to their relatively high operating frequencies (MHz). An ideal resonator is lossless with an infinite Q . Naturally, various physical phenomena exist to siphon energy from the device, limiting its ultimate performance defined by fundamental Akhiezer limit (AKE) phonon-phonon interactions.

[0091] One physical phenomenon that siphons energy from the device is energy loss from the resonator to the substrate. To overcome this energy loss, a phononic crystal may be provided in the substrate to provide a bandgap to impede energy transfer from the resonator to the substrate. A phononic crystal is a structure composed of stacked acoustically mismatched layers (superlattice) or a tessellation of periodic inclusions in an elastic medium. Analogous to a photonic crystal for electromagnetic radiation, the mismatch of acoustic impedance between the layers or inclusions reflects waves, introducing wave interference which creates the bandgap.

[0092] Current methods of incorporating a phononic crystal into a MEMS device comprise locating the device within a substrate, and the substrate surrounding the device

composes these inclusions for providing the bandgap. In other words, current systems provide phononic crystals in the same plane as the MEMS device to acoustically decouple the MEMS device from the surrounding substrate. This design is not optimal for micro- or nano-scale devices and is also not optimal for altering the characteristics of both the substrate and the device to maximize the quality factor (" Q ") and $f \cdot Q$ product. The present disclosure provides a novel MEMS device design that solves the inherent limitations of in-plane phononic crystal designs. As will be discussed in greater detail below, the present systems and devices can provide a MEMS device having a quality factor in excess of 2,000,000.

[0093] Various devices and methods are disclosed for providing an acoustically decoupled microelectromechanical system devices anchored upon phononic crystals, and exemplary embodiments of the devices and methods will now be described with reference to the accompanying figures.

[0094] FIG. 1 is a cross-sectional view of an acoustically decoupled device 100 comprising a resonator 102 anchored upon a handle layer 104, according to an exemplary embodiment of the present disclosure. In some embodiments, the resonator 102 may be connected to the handle layer 104 by a pedestal 106. In some embodiments, the handle layer 104 may comprise a phononic crystal structure, shown in the figure by the plurality of inclusions 108 creating the phononic crystal structure. As can be seen in the figure, the resonator 102 and the handle layer 104 are non-coplanar. By moving the resonator 102 and handle layer 104 into separate planes, the inclusions 108 may reside between the resonator 102 and the surface of the handle layer 104, i.e., the inclusions 108 may be covered at least in part by the resonator 102. This provides a substantial improvement over previous in-plane or coplanar systems, as coplanar systems require the inclusions 108 of the phononic crystal to be disposed outside the footprint of the resonator 102.

[0095] In some embodiments, the inclusions 108 may be proximate the pedestal 106. In some embodiments, additional circuitry, including but not limited to circuitry for electrodes, including sense and/or drive electrodes, may be disposed between the resonator 102 and the surface of the handle layer 104, i.e., the circuitry may be covered at least in part by the resonator 102. In other embodiments, circuitry may be disposed on the handle layer 104 in an area outside of the inclusions 108 of the handle layer 104. Exemplary embodiments with electrodes are discussed in greater detail herein. With the current, non-coplanar design, more space is provided around the phononic crystal structure than in a coplanar configuration. As will be appreciated, the phononic crystal structure of the handle layer 104 may be distorted, or altered, to make room for the pedestal 106, electrodes, bonding areas, and/or circuitry. In

other words, the inclusions 108 may be adjusted to provide room for each of these features or any other feature disposed between the handle layer 104 and the resonator 102. Therefore, when reference is made to a phononic crystal in this disclosure, it will be understood that, in some embodiments, the phononic crystal structure may be altered in such a way as to include any of these features.

[0096] As will be appreciated, the resonator 102 may be any one of a number MEMS devices, including but not limited to timing resonators, accelerometers, and/or gyroscopes. The non-coplanar design of the present systems may provide distinct benefits for gyroscope devices. In some gyroscope architectures, for example, the quality factor of Coriolis-coupled resonant modes should match. For various designs, this condition implies a centrally-supported gyroscope. This condition is inherently met when placing the phononic crystal structure (i.e., handle layer 104) in a different plane than the MEMS device (i.e., resonator 102) wherein the two features are connected by a pedestal 106.

[0097] The resonator 102 may comprise any material that can be commonly micromachined, including but not limited to polycrystalline silicon, silicon carbide, polycrystalline silicon carbide, germanium, silicon nitride, silicon dioxide, aluminum nitride, alumina, fused quartz and/or diamond. Additionally, the dimensions of the resonator 102 may be manipulated to optimize requirements for the MEMS device. For example and not limitation, the thickness of the resonator 102 may be altered to optimize frequency requirements. In some embodiments, the thickness of the resonator 102 may be from between 1 μ m and 500 μ m. In some embodiments, the width of the resonator 102 may also be altered to optimize frequency requirements for the MEMS device. For example, if the resonator is square or rectangular, the width and/or length of the resonator 102 may be altered to adjust the resonant frequency. In some embodiments, the width and/or length of the resonator 102 may be from between 100 μ m and 5mm. In some embodiments, the resonator 102 may be circular, and it is contemplated that the diameter of a circular resonator 102 may be from between 100 μ m and 5mm.

[0098] The handle layer 104 may comprise any material that can be commonly micromachined, including but not limited to polycrystalline silicon, silicon carbide, polycrystalline silicon carbide, germanium, silicon nitride, silicon dioxide, aluminum nitride, alumina, fused quartz, and/or diamond. As described herein, because the resonator 102 and the handle layer 104 are non-coplanar, the material of the handle layer 104 (i.e., substrate) is not required to be the same material as the resonator 102. Additionally, the dimensions of the handle layer 104 may be manipulated to optimize requirements for the substrate. For

example and not limitation, the thickness of the handle layer 104 can be optimized to prevent the propagation of out-of-plane energy, as will be discussed in greater detail herein. Again, because the resonator 102 and the handle layer 104 are non-coplanar, the thickness of the handle layer 104 is not required to be the same thickness of the resonator 102. In some embodiments, the thickness of the handle layer 104 may be from between 100 μ m and 1500 μ m. As will be described in greater detail below, the thickness of the handle layer 104 may correspond to a wavelength of an acoustic wave propagating through the handle layer 104 material corresponding to the resonator 102 frequency. In some embodiments, the width of the handle layer 104 may also be altered to optimize requirements the substrate. This optimization may include, for example, optimizing the overall footprint of the acoustically decoupled device 100. In some embodiments, the width of the handle layer 104 may be from between 30 μ m and 30mm. In some embodiments, holes (not shown in the figure) may be etched on the handle layer 104 at a location covered by the resonator 102 so as to reduce the amount of stiction force the resonator 102 may be required to overcome in the case of high shocks to the device. In some embodiments, these etched holes may improve the shock resistance of the acoustically decoupled device 100. In some embodiments, trenches, divots, and/or other cavities may be disposed on the handle layer 104 at a location covered by the resonator 102 so as to reduce the amount of stiction force. These structures may be disposed upon the handle layer by etching or by any other method known by those having skill in the art.

[0099] In some embodiments, the pedestal 106 may connect to the resonator 102 at the center of the resonator 102. In some embodiments, a resonator 102 may be connected to the handle layer 104 by more than one pedestal 106. For example, a single resonator 102 may be anchored to a handle layer 104 not at a centrally-placed pedestal 106, but instead by two or more pedestals 106 connecting the resonator 102 to the handle layer 104. In some embodiments, a single handle layer 104 may support a plurality of resonators 102. For example and not limitation, a single handle layer 104 may comprise a phononic crystal structure, and a plurality of pedestals 106 may be dispersed between the inclusions 108 of the phononic crystal structure, each pedestal 106 connecting at least one resonator 102 to the shared handle layer 104. Such an embodiment is possible because the systems described herein allow a resonator 102 to cover (or reside above or below) at least some inclusions 108 on the handle layer 104. This may be a significant improvement over co-planar systems. In co-planar systems, two resonators 102 may not be placed adjacent to each other without at

least some inclusions 108 between the two resonators to acoustically decouple them. This is another space-conserving capability of the present systems.

[00100] FIG. 2 is a perspective view of an acoustically decoupled device 100 comprising a resonator 102 anchored upon a handle layer 104, according to an exemplary embodiment of the present disclosure. A resonator 102 may comprise a perimeter edge 202. The perimeter edge 202 may be separated from the handle layer 104 by a gap 204. The gap 204 may be disposed between the resonator 102 and the handle layer 104 from the perimeter edge 202 to the pedestal 106. In some embodiments, the perimeter edge 202 of the resonator 102 may be circular, as shown in the figure. A perimeter edge 202 that is circular defines a disk-shaped resonator 102. In other embodiments, the perimeter edge 202 of the resonator may comprise other shapes, depending on the use of the device. These perimeter edge 202 shapes may include ovals, squares, rectangles, scalloped designs, and/or other shapes depending on the use of the device. In some embodiments, the handle layer 104 may be circular (as shown in FIG. 1). In other embodiments, the handle layer 104 may be any other shape as described above for the resonator 102. In some embodiments, the handle layer 104 may comprise a greater footprint than the resonator 102, thereby protecting the resonator 102 at the perimeter edge 202 and providing room for additional inclusions 108, circuitry, or any other feature necessary for the device. In the case of a circular resonator 102 and a circular handle layer 104, the diameter of the handle layer 104 may be, in some embodiments, greater than the diameter of the resonator 102.

[00101] In some embodiments, a resonator 102 may comprise a surface layer 206 disposed on the side opposite from the pedestal 106 (shown in FIG. 1). In some embodiments, the surface layer 206 may be flat, as shown. The surface layer 206 may also comprise a three-dimensional topography. As described above, the width, length, or diameter of a resonator 102 may be from between 100 μ m and 5mm. In some embodiments, this range of 100 μ m to 5mm may be a length across the surface layer 206 of the resonator 102 from a first point at the perimeter edge 202 to a second point at the perimeter edge, passing over a centrally-placed pedestal 102 (not shown in FIG. 2).

[00102] FIG. 3 is a side perspective view of an acoustically decoupled device 100 comprising a resonator 102 anchored upon a handle layer 104 by a pedestal 106, according to an exemplary embodiment of the present disclosure. As described above, in some embodiments, a resonator 102 may be connected to a handle layer 104 by a pedestal 106. The inclusion of an anchor layer, i.e., the pedestal 106, may provide space to incorporate more inclusions 108 (shown in FIGs. 1-2) in the phononic crystal structure of the handle layer

104, additional circuitry, or any other feature and/or component described herein. FIG. 3 depicts an exemplary gap 204 disposed between the perimeter edge 202 of a resonator 102 and the handle layer 104. In some embodiments, the gap 204 is created due to the pedestal 106 having a smaller footprint (diameter in the case of circular devices) than the resonator 102. In some embodiments, a gap 204 may be uniform. For example and not limitation, the gap 204 between the resonator 102 and the handle layer 104 may be consistent at any location on the surfaces of either component. In some embodiments, the gap 204 between the perimeter edge 202 and the handle layer 104 may be uniform along the entirety of the perimeter edge 202. In other embodiments, the gap 204 may be non-uniform. For example and not limitation, the handle layer 104, the resonator 102, or both may comprise a three-dimensional shape. In these embodiments, the gap 204 may be smaller at some positions than at other positions between the resonator 102 and the handle layer 104.

[00103] In some embodiments, the pedestal 106 may comprise a conical frustum shape, as shown in the figure. In other embodiments, alternative shapes for the pedestal 106 are contemplated, including but not limited to cylinders. The dimensions of the pedestal depends on the desired characteristics of the device. As will be described below, anchor loss is a source of energy loss for an acoustically decoupled device 100 comprising a resonator 102 connected to a handle layer 104 by a pedestal 106. While shrinking the size of the pedestal 106 monotonically mitigates anchor losses, the size of the pedestal 106 cannot be made excessively small to ensure resilience against shock and vibration. Similarly, elongation of the pedestal 106 offers a measure of isolation, but excessive elongation may compromise structural integrity. In some embodiments, the pedestal 106 may have a height (or length from a first end proximate the resonator 102 and a second end proximate the handle layer 104) of from between 1 μ m to 500 μ m. In some embodiments, the height of the pedestal 106 corresponds to the length of the gap 204. However, it is contemplated that the pedestal 106 may be disposed in a recess either in resonator 102, the handle layer 104, or both. In an embodiment wherein the pedestal 106 connects to the resonator 102 or the handle layer 104 at a recess in either component, the gap 204 at the perimeter of the resonator 102 may be shorter than the height of the pedestal 106. Additionally, it is contemplated that the pedestal 106 may be disposed upon a platform either on the resonator 102, the handle layer 104, or both. In an embodiment wherein the pedestal 106 connects to the resonator 102 or the handle layer 104 at a platform on either component, the gap 204 at the perimeter of the resonator 102 may be larger than the height of the pedestal 106. Altering the height of the pedestal 106 and/or the gap 204 size may provide another parameter to control acoustic decoupling

between the resonator 102 and the handle layer 104; the planes of the resonator 102 and the handle layer 104 may be separated even farther by increasing the pedestal 106 height and/or the gap 204 size.

[00104] In some embodiments, the width of a pedestal 106 (or diameter in the case of a circular pedestal 106) may be from between 1 μ m and 500 μ m. In some embodiments, the width of the pedestal 106 may be greater at one end than the other (for example in the case of a conical frustum shape), and either end of the pedestal 106 may fall within that range or any other range that may be beneficial for the device design, as will be appreciated. In some embodiments, the width or diameter of a pedestal 106 may be described in the terms of a percentage of the width or diameter of a resonator 102. For example, in some embodiments, the pedestal 106 may be from between 1% and 90% of the diameter of the resonator 102. In some embodiments, the pedestal 106 may be from between 1% and 10% of the diameter of the resonator 102. The pedestal 106 may be manufactured in whole or in part out of any of the materials described herein, including but not limited to polycrystalline silicon, silicon carbide, polycrystalline silicon carbide, germanium, silicon nitride, silicon dioxide, aluminum nitride, alumina, fused quartz, and/or diamond.

[00105] As described above, placing the resonator 102 and the handle layer 104 in different planes can help alleviate many of the pitfalls of coplanar integration for in-plane phononic crystal devices. The benefits of an out-of-plane, non-coplanar device may include varying the material composition and dimensions of the resonator 102 and handle layer 104, this due to the resonator 102 not being manufactured along one substrate surface. However, other concerns, such as the dissipation mechanisms of the device, must be addressed before hitting the Akhiezer limits for the MEMS devices. Due to a bulk acoustic wave disk resonator's relatively high operating frequency, in vacuum, disks typically suffer from thermoelastic dissipation and anchor losses.

[00106] Thermoelastic dissipation ("TED") occurs in any material that experiences thermal expansion. Three TED operating regimes exist: isothermal, adiabatic, or maximally dissipative (Debye). In elliptical bulk acoustic wave disk resonators at the MEMS scale, the resonant mechanical frequency is highly disparate from the principal thermal mode frequencies, pushing the device into the deep adiabatic regime, minimizing TED to elevate Q_{TED} to 14M for the breathing mode in FEM simulation.

[00107] Anchor loss remains as one of the most conspicuous sources of loss, adding unpredictability to the limits of quality factor. In centrally-anchored disk resonators (such as those described herein with a single pedestal 106), the suppression of anchor loss is

particularly difficult due to large elastic strain energy density in the vicinity of the pedestal 106. Substrate-decoupling elements may be incorporated into the device layer; however, this comes at the expense of increased TED due to additional strain at the sites of the occlusions. Therefore, it may be beneficial to implement a 3D design in which the substrate-decoupling elements lie in the handle layer 104 beneath the disk (resonator 102), leaving the disk unencumbered by TED while eliminating anchor losses. This is where a handle layer 104 comprising a phononic crystal structure may aid to increase the efficiency of the device.

[00108] A phononic crystal is a structure composed of stacked acoustically mismatched layers (superlattice) or a tessellation of periodic inclusions in an elastic medium. Analogous to a photonic crystal for electromagnetic radiation, the mismatch of acoustic impedance between the layers or inclusions reflects waves, introducing wave interference which creates the bandgap of the phononic crystal. Two critical parameters determine the behavior and characteristics of the bandgap: the center frequency and bandgap width. The center frequency is defined principally by the characteristic unit-cell length a , typically on the order of the propagating wave's wavelength. The width of the bandgap is heavily affected by the acoustic impedance discrepancy between the propagating medium and the inclusions. Filling factor β (the ratio of the area of the inclusions to the area of the unit-cell) is the primary parameter influencing the width of the gap. A structure's bandgap behavior can be described by its fa product [Hz·m], as wavelength and frequency are inversely proportional. With increasing filling factor, the bandgap widens.

[00109] Any number of lattice structures for a phononic crystal may be employed to impede energy transfer from the resonator 102 to the substrate. Some examples of these lattice structures include, but are not limited to, honeycomb lattices and square lattices. FIGs. 4A and 4B depict an exemplary honeycomb lattice structure. The unit-cell, when placed in a rectangular lattice, creates a honeycomb tessellation. FIG. 4A depicts an exemplary honeycomb tessellation (with inclusions 108). FIG. 4B illustrates an exemplary unit-cell length 402, as described above, for a honeycomb lattice.

[00110] FIG. 5 is a graph showing the bandgap 502 for a honeycomb lattice structure. The X-axis is the filling factor. As shown in the Y-axis, the fa product [Hz·m] depends on the filling factor. For a given fa product and a filling factor β , the waves can either propagate (indicated as the colored region in FIG. 5) or not (indicated by the striped region in FIG. 5). All the points within the striped region form the bandgap which depends non-trivially on f , a , and β . The honeycomb lattice has been shown to provide the widest bandgap 502 at the lowest filling factor (the ratio of the area of the inclusions to the area of the unit-

cell). As will be appreciated, when decoupling a resonator 102 from the substrate, a wider bandgap is desired to impede energy transfer. Also, a wide bandgap at a low filling factor may be desired for acoustically decoupled device 100: a wide bandgap may be maintained while providing more substrate (less inclusions 108) and thus more structural integrity for the device 100.

[00111] As described above, other lattice structures are possible. FIG. 6A depicts an exemplary square lattice structure (with inclusions 108). FIG. 6B illustrates an exemplary unit-cell length 602 for a square lattice. FIG. 7 is a graph showing the bandgap 702 for a square lattice structure. As can be seen, the square lattice structure produces a bandgap 702 beginning at a filling factor of approximately 0.4. The phononic crystal structure of the handle layer 104 of any of the embodiments described herein may be a honeycomb lattice, a square lattice, or any other phononic crystal lattice known by those having skill in the art. In some embodiments, the unit-cell length a (e.g., unit-cell lengths 402, 602) for a lattice structure may be from between 10 μ m and 1500 μ m. In some embodiments, the lattice structure must be placed in such a way as to preserve the resonant mode symmetry to minimize any frequency split between the gyroscopic resonant modes.

[00112] Although the phononic crystal design addresses the in-plane issues associated with energy lost to the substrate, other factors may lead to energy loss. Proper vertical out-of-plane decoupling is also a factor that may be addressed to avoid anchor loss. In some embodiments, vertical confinement can be achieved by altering the thickness of the handle layer 104 (or the phononic crystal structure). Handle layer 104 thickness may affect Q_{ANC} , and a relationship exists between the thickness of the handle layer 104 and the wavelength of an acoustic wave through the resonator 102, as determined by the frequency of the resonator 102 and the speed of wave propagation through the handle layer 104. FIG. 8 is a graph showing the relationship of handle layer 104 thickness to Q_{ANC} . As can be seen, at $\lambda/4$, wave interference creates a standing wave with a node at the suspended end of the device (i.e., at the pedestal 106). Here, λ equals the wavelength of an acoustic wave propagating through the handle layer 104, and λ corresponds to the frequency of the resonator's 102 resonant mode. Specifically, the thickness H of the handle layer 104 may be defined as $H \sim \frac{1}{4} * \frac{1}{f} * \sqrt{\frac{E}{\rho}}$ where E and ρ are the Young's modulus and density of the handle layer 104 and f is the resonant frequency of the resonator 102. In concert with a phononic crystal, anchor loss can be made negligible by providing a handle layer 104 thickness of $\lambda/4$. Therefore, in some

embodiments, the handle layer 104 thickness may be approximately $\lambda/4$ for any device described herein. Other thicknesses are contemplated, and the functionality of the device is not limited to only devices having a handle layer 104 with a thickness of approximately $\lambda/4$. Additionally, handle layer 104 thickness can be optimized independently of the characteristics of the phononic crystal structure (i.e., independent of unit-cell length a and filling factor β).

[00113] In perfectly matched layer (PML) simulation, the tandem of quarter wavelength matching and the phononic crystal may offer excellent substrate decoupling. Another consideration that may also affect anchor loss and thermoelastic dissipation is the number of unit-cells within the phononic crystal. Placing more phononic crystal unit-cells in the decoupling layer may provide greater impedance of propagating waves, improving energy confinement. In some embodiments, when a sufficient number of unit-cells are placed around the pedestal 106 of the device, the resonator 102 can be made substrate “deaf,” leaving the device limited exclusively by intrinsic dissipation mechanisms such as thermoelastic dissipation and Akhiezer limit. FIG. 9 is a graph showing the relationship between unit-cell quantity and quality factor Q . As shown, as more unit-cells are included in the phononic crystal, Q_{Anchor} 902 surpasses Q_{TED} 904 and finally $Q_{Akhiezer}$ 906. When the phononic crystal approaches three unit-cells, the Q_{Anchor} 902 approaches the Akhiezer limit. Therefore, in some embodiments, the phononic crystal of the handle layer 104 may comprise at least three unit-cells. In some embodiments however, it is contemplated that the handle layer 104 may comprise less than three unit-cells.

[00114] FIGs. 10A and 10B depict an acoustically decoupled device 100 with a plurality of electrodes 1002, according to an exemplary embodiment of the present disclosure. As described above, the current design provides an opportunity to dispose electrodes 1002 about the resonator 102. FIG. 10A is a perspective view of an exemplary an acoustically decoupled device 100 comprising a resonator 102 and a plurality of electrodes 1002, according to an exemplary embodiment of the present disclosure. In some embodiments, one or more electrodes 1002 may be positioned about the resonator 102 in the same plane as the resonator 102. As will be appreciated, in some embodiments these electrodes 1002 may be drive electrodes, sense electrodes, and/or any combination thereof. In some embodiments, a drive electrode 1002 may actuate the resonator 102 by providing a drive voltage signal to the resonator 102.

[00115] FIG. 10B is a cross-sectional view of an acoustically decoupled device 100 with a resonator 102 connected to a handle layer 104 by a pedestal 106, wherein the device further comprises one or more electrodes 1002, according to an exemplary embodiment of the present disclosure. In some embodiments, a device may comprise one or more electrodes 1002 disposed in the same plane as a resonator 102. In some embodiments, and as described above, the resonator 102 may be connected to the handle layer 104 via a pedestal 102. To position the electrodes 1002 in the same plane as the resonator 102, in some embodiments the electrodes 1002 may be connected to the handle layer 104 by an electrode pedestal 1004. A benefit of the presently described systems is the opportunity to dispose the phononic crystal structure between the resonator pedestal 106 and the electrode pedestals 1004. For example, FIG. 10B shows an inclusion 108 for the phononic crystal structure of the handle layer 104 disposed between the pedestal 106 and the electrode pedestal 1004. Such an embodiment is not possible with coplanar designs. In some embodiments, an electrode pedestal 1004 may be disposed at a location between inclusions 108 of the phononic crystal structure.

[00116] In some embodiments, a capacitive gap 1006 may be disposed between the resonator 102 and an electrode 1002. It is contemplated that the capacitive gap 1006 may be from between 100nm and 10 μ m. In some embodiments, the capacitive gap 1006 may be small so as to increase the electromechanical coupling of the system. The presently described systems allow this small gap size because, as described above, the phononic crystal structure of the handle layer 104 may be disposed between the resonator pedestal 106 and an electrode pedestal 1004. In some embodiments, the capacitive gap 1006 may be from between 100nm and 500nm.

EXPERIMENTAL SECTION

[00117] The following section discusses an experiment performed on an exemplary acoustically decoupled device, as described herein. With a large stiffness and low average Grüneisen parameter, silicon carbide was determined to be a candidate for ultra-high Q devices as it possesses an $f.Q_{AKE}$ of 6.4×10^{14} Hz, over $30\times$ higher than silicon's. Silicon carbide has many polytypes with cubic, hexagonal, and rhombohedral symmetries. Among commercially available polytypes, atomically smooth monocrystalline 4H-SiC (hexagonally symmetric) wafers exhibit a great degree of isotropicity, making the polytype well-suited to demonstrate ultra-high Q gyroscopic modes in center-supported resonators; therefore, this material was chosen for the tested resonator devices. Notably, the $m=3$ bulk elliptical

gyroscopic modes are fully degenerate in 4H-SiC, critical to mode-matched gyroscopic operation to take full advantage of Q .

[00118] SiCOI substrates with 100 μ m SiC device layer on a 500 μ m Si handle layer separated by a thermally grown silicon oxide interlayer were custom-made for the experimentation. To do so, a SiC wafer for the resonator and a silicon wafer for the handle layer were provided. Thermal oxides on both wafers were used as interlayers for bonding as well as buried layers for SiCOI substrates for its higher film density than those of any other deposited oxides. The 4H-SiC wafer comprised a Si-face on one side and a C-face on the other side. The C-face grows thermal oxide at least 8 times faster than Si-face under the same wet oxidation conditions. Thus, Si wafers were fusion bonded on the C-face of 4H-SiC. On-axis 4H-SiC and Si wafers were RCA cleaned and thermally wet oxidized at 1100° C for 6 hours. Then, thermal oxide layers were kiss polished to keep the surface pristine and to reduce the surface roughness to below 1.0nm RMS. Wafers were brought into contact together after an O₂/N₂ plasma treatment, and annealed in an oven at 250° C. Subsequently, bonded wafers were annealed again at 1100° C to permanently dehydrate and dehydroxylate the buried oxide (BOX) layer. With this fabrication process, 4" and 6" SiCOI substrates with SiC device layer thickness ranging from 10 to 500 μ m and Si handle layer thickness ranging from 300 μ m to 1mm can be fabricated with a total thickness variation (TTV) near 1 μ m.

[00119] After deposition of a Ti/Cu seed layer, the electroplated nickel mask was formed to define the disk resonators; the $\lambda/4$ handle layer thickness discussed above prescribed the disk diameter to place the mode of interest at 5 MHz. Nickel was used as a hard mask for the subsequent SiC DRIE step, because of its high selectivity over SiC, near 100:1, dwarfing that of SiO₂ (~1:1). The disks were etched in an STS AOE chamber using a mixture of sulfur hexafluoride (SF₆) and Argon (Ar) with a large DC bias voltage. Carbon atoms in the SiC react with SF₆, forming an inherent passivation layer (C_xF_y), enabling anisotropic etching. The remaining nickel mask and any deposition on the sidewall were removed by wet etch.

[00120] The phononic crystal geometry was then defined via backside alignment to the SiC layer and etched by a standard Bosch process. This backside 500 μ m through-etch produces large amounts of Teflon which can exacerbate anchor losses if not properly cleaned. Using a material with higher acoustic velocity for the handle layer may relax this constraint. Finally, the sacrificial buried oxide layer was laterally etched with HF through the phononic crystal structures doubling as release holes, self-aligning the pedestal with a size controlled by release time. The process yielded a breathing mode disk resonator (1540 μ m) supported by

a SiO₂ pedestal 100μm (6% of disk size) in diameter. The resonator was anchored upon a phononic crystal comprising three unit-cells, engineered with a unit cell length of 405μm to decouple the 5MHz radial mode. The pedestal was 2μm tall, separating the disk resonator from the silicon handle layer below.

[00121] The fabricated disks were then mounted upon ultrasonic lithium niobate shear mode piezostages, adhered with Crystalbond. The setup was then placed in a vacuum chamber and pumped down to sub-mTorr. S21 frequency response measurements were taken with a laser Doppler vibrometer in conjunction with a network analyzer. Three devices of varying diameter were tested, each aiming to position the radial, $m=3$, and $m=4$ modes at 5 MHz (1.56mm, 1.7mm, and 2.21mm, respectively).

[00122] FIG. 11 is a graph presenting the results of testing an exemplary disk resonator having a diameter of 1.56mm. As can be seen in the graph, the 1.56mm disk resonator displayed a breathing mode Q of 3,700,000 at 5 MHz. To date, this is the highest fQ product (1.85×10^{13} Hz) measured in SiC resonators. Simulated with $Q_{ANC}=350M$ and a limiting $Q_{TED}=14M$ at 5 MHz, the Q discrepancy arises due to sidewall defects. In contrast, a similar disk resonator (5mm diameter) anchored upon an unmodified silicon substrate (without a phononic crystal) with smaller anchor diameter (3% of the device diameter) demonstrated a Q of $\sim 1,000,000$ at 1.7 MHz. Despite its larger size (less TED) and diminished pedestal area, the lack of any substrate decoupling bounds Q for the 5mm disk resonator to smaller values.

[00123] As described above, sidewall defects may lead to Q discrepancies. SEMs of the sidewall of the resonators tested show striations on the micron scale. FIG. 12 is a graph showing the relationship between striation radius for the resonator and Q_{TED} . As can be seen, Q_{TED} monotonically decreases with increasing striation size, flattening to Q s in the millions. Horizontal striations appear when etching is disrupted and restarted, and these striations are more easily obviated. Vertical striations however, may arise from a fusion of different sources: non-uniformities in the nickel mask that propagate during DRIE, in combination with charging in the passivation layer that segregates and directs plasma species imperfectly, may result in a striated sidewall. In simulation, striations are modeled as a hemi-cylindrical defect on the sidewall of the disk, introducing additional strain coupling to thermal fields. The results of this model are presented in FIG. 12. The “current status” located on the map indicates expected defects for the resonators tested in described experimentation.

[00124] FIG. 13 is an atomic force micrograph of the sidewall of the disk resonators tested in the discussion above. The SiC disk resonators, as tested, show defects ranging from 1-3μm in lateral dimension. TED simulations incorporating these defects yield a Q_{TED} of 4.5

M for the radial mode at 5MHz (as shown in FIG. 11), confirming measurement as a TED limited mode.

[00125] The systems described herein provide a novel design that, with nano-scale sidewall roughness fabricated on SiCOI, offer a pathway to extremely high Q s. Monocrystalline SiC bulk acoustic wave resonators offer low intrinsic material dissipation. Consequently, implementing a 3D substrate-decoupled handle layer—leaving the disk itself unblemished—unlocks the possibility of fabricating disk resonators with Q 's tethered to intrinsic quantum limits in excess of 100M. Additionally, the resonators tested, even with potential vertical striations, displayed a breathing mode Q of 3,700,000 at 5 MHz. To date, this is the highest fQ product (1.85×10^{13} Hz) measured in SiC resonators.

[00126] It is to be understood that the embodiments and claims disclosed herein are not limited in their application to the details of construction and arrangement of the components set forth in the description and illustrated in the drawings. Rather, the description and the drawings provide examples of the embodiments envisioned. The embodiments and claims disclosed herein are further capable of other embodiments and of being practiced and carried out in various ways. Also, it is to be understood that the phraseology and terminology employed herein are for the purposes of description and should not be regarded as limiting the claims.

[00127] Accordingly, those skilled in the art will appreciate that the conception upon which the application and claims are based may be readily utilized as a basis for the design of other structures, methods, and systems for carrying out the several purposes of the embodiments and claims presented in this application. It is important, therefore, that the claims be regarded as including such equivalent constructions.

[00128] Furthermore, the purpose of the foregoing Abstract is to enable the United States Patent and Trademark Office and the public generally, and especially including the practitioners in the art who are not familiar with patent and legal terms or phraseology, to determine quickly from a cursory inspection the nature and essence of the technical disclosure of the application. The Abstract is neither intended to define the claims of the application, nor is it intended to be limiting to the scope of the claims in any way. Instead, it is intended that the invention is defined by the claims appended hereto.

What is claimed is:

1. A device comprising:
 - a resonator comprising a perimeter edge;
 - a handle layer comprising a phononic crystal structure;
 - a pedestal disposed between the resonator and the handle layer, the pedestal connecting the resonator to the handle layer; and
 - a gap disposed between the resonator and the handle layer.
2. The device of claim 1, wherein the resonator and the handle layer are not coplanar.
3. The device of claim 1, wherein the handle layer comprises:
 - a first side and a second side, wherein the first side is proximate the pedestal; and
 - a handle layer thickness disposed between the first side and the second side, wherein the handle layer thickness is approximately $\lambda/4$, where λ is equal to a wavelength of an acoustic wave propagating through the handle layer corresponding to a resonator frequency.
4. The device of claim 1, wherein the handle layer comprises a plurality of structures etched into the handle layer.
5. The device of claim 1, wherein the handle layer comprises a lattice structure having a plurality of unit-cells.
6. The device of claim 5, wherein the lattice structure comprises at least three unit-cells.
7. The device of claim 5, wherein the lattice structure is a honeycomb lattice structure having a unit-cell length of from between 10 μm and 1500 μm .
8. The device of claim 1, wherein the resonator is a gyroscope.
9. The device of claim 1, wherein the perimeter edge of the resonator is circular.
10. The device of claim 1, wherein the perimeter edge of the resonator is square or rectangular.

11. The device of claim 9, wherein the resonator comprises a diameter of from between 100 μ m and 5mm.
12. The device of claim 9, wherein the resonator comprises a first diameter, wherein the pedestal comprises a second diameter, and wherein the second diameter is from between 1% and 10% of the first diameter.
13. The device of claim 10, wherein the resonator comprises a width and/or length of from between 100 μ m and 5mm.
14. The device of claim 1, wherein the pedestal comprises:
a first end and a second end, wherein the first end is proximate the resonator, and wherein the second end is proximate the handle layer; and
a length, wherein the length is disposed between the first end and the second end, and wherein the length is from between 1 μ m to 500 μ m.
15. The device of claim 1, wherein the pedestal comprises at least one of a conical frustum or a cylindrical shape.
16. The device of claim 1, wherein the resonator comprises at least one of silicon carbide, aluminum nitride, polycrystalline silicon carbide, polycrystalline silicon, diamond, or fused quartz.
17. The device of claim 1, wherein the resonator comprises a first material composition, wherein the handle layer comprises a second material composition, and wherein the first material composition is not the same as the second material composition.
18. The device of claim 1, wherein the device further comprises:
an electrode connected to the handle layer, wherein the electrode is disposed proximate the perimeter edge of the resonator; and
a capacitive gap disposed between the electrode and the resonator.
19. The device of claim 18, wherein the capacitive gap is from between 100nm and 500nm.

20. The device of claim 18, wherein the electrode is connected to the handle layer by an electrode pedestal.
21. The device of claim 1, wherein the resonator has a quality factor greater than 2,000,000.
22. A MEMS device comprising:
a resonator gyroscope having a perimeter edge;
a handle layer comprising a phononic crystal structure;
a pedestal disposed between the resonator gyroscope and the handle layer, the pedestal connecting the resonator gyroscope to the handle layer; and
a gap disposed between the resonator gyroscope and the handle layer.
23. The device of claim 22, wherein the resonator gyroscope and the handle layer are not coplanar.
24. The device of claim 22, wherein the handle layer comprises:
a first side and a second side, wherein the first side is proximate the pedestal; and
a handle layer thickness disposed between the first side and the second side, wherein the handle layer thickness is approximately $\lambda/4$, where λ is equal to a wavelength of an acoustic wave propagating through the handle layer corresponding to a resonator gyroscope frequency.
25. The device of claim 22, wherein the handle layer comprises a plurality of structures etched into the handle layer.
26. The device of claim 22, wherein the handle layer comprises a lattice structure having a plurality of unit-cells.
27. The device of claim 26, wherein the lattice structure comprises at least three unit-cells.
28. The device of claim 26, wherein the lattice structure is a honeycomb lattice structure having a unit-cell length of from between 10 μm and 1500 μm .

29. The device of claim 22, wherein the perimeter edge of the resonator gyroscope is circular.
30. The device of claim 29, wherein the resonator gyroscope comprises a diameter of from between 100 μ m and 5mm.
31. The device of claim 29, wherein the resonator gyroscope comprises a first diameter, wherein the pedestal comprises a second diameter, and wherein the second diameter is from between 1% and 10% of the first diameter.
32. The device of claim 29,
wherein the handle layer is cylindrical,
wherein the resonator gyroscope comprises a first diameter,
wherein the handle layer comprises a second diameter, and
wherein the second diameter greater than the first diameter.
33. The device of claim 22, wherein the perimeter edge of the resonator gyroscope is square or rectangular.
34. The device of claim 33, wherein the resonator gyroscope comprises a width and/or length of from 100 μ m and 5mm.
35. The device of claim 22, wherein the pedestal comprises:
a first end and a second end, wherein the first end is proximate the resonator gyroscope, and wherein the second end is proximate the handle layer; and
a length, wherein the length is disposed between the first end and the second end, and wherein the length is from between 1 μ m to 500 μ m.
36. The device of claim 22, wherein the pedestal comprises at least one of a conical frustum or a cylindrical shape.
37. The device of claim 22, wherein the resonator gyroscope comprises at least one of silicon carbide, aluminum nitride, polycrystalline silicon carbide, polycrystalline silicon, diamond, or fused quartz.

38. The device of claim 22, wherein the device further comprises:
an electrode connected to the handle layer, wherein the electrode is disposed proximate the perimeter edge of the resonator gyroscope; and
a capacitive gap disposed between the electrode and the resonator gyroscope.
39. The device of claim 38, wherein the capacitive gap is from between 100nm and 500nm.
40. A MEMS gyroscope comprising:
a disk resonator comprising a perimeter edge and having a first diameter;
a handle layer comprising a phononic crystal structure, wherein the handle layer comprises a thickness of approximately $\lambda/4$, and wherein λ is equal to a wavelength of an acoustic wave propagating through the handle layer corresponding to a disk resonator frequency; and
a pedestal disposed between the disk resonator and the handle layer, the pedestal connecting the disk resonator to the handle layer, wherein the pedestal comprises a second diameter, and wherein the second diameter is less than the first diameter.
41. The gyroscope of claim 40, wherein the handle layer comprises a plurality of structures etched into the handle layer.
42. The gyroscope of claim 40, wherein the handle layer comprises a lattice structure having a plurality of unit-cells.
43. The gyroscope of claim 42, wherein the lattice structure is a honeycomb lattice structure having a unit-cell length of from between 10 μ m and 1500 μ m.
44. The gyroscope of claim 40, wherein the disk resonator comprises at least one of silicon carbide, aluminum nitride, polycrystalline silicon carbide, polycrystalline silicon, diamond, or fused quartz.
45. The gyroscope of claim 40 further comprising:
a plurality of electrodes disposed proximate the perimeter edge of the disk resonator;
and

a capacitive gap disposed between the disk resonator and each electrode of the plurality of electrodes.

46. The gyroscope of claim 45, wherein the capacitive gap is from between 100nm and 500nm.

47. The gyroscope of claim 45, wherein at least part of the plurality of electrodes are configured to actuate the disk resonator.

48. The gyroscope of claim 40, wherein the disk resonator has a quality factor greater than 2,000,000.

49. A MEMS gyroscope comprising:

a disk resonator gyroscope comprising a perimeter edge and having a first diameter;
a handle layer comprising a phononic crystal structure, wherein the handle layer comprises a thickness of approximately $\lambda/4$, and wherein λ is equal to a wavelength of an acoustic wave propagating through the handle layer corresponding to a disk resonator gyroscope frequency;

a pedestal disposed between the disk resonator gyroscope and the handle layer, the pedestal connecting the disk resonator gyroscope to the handle layer, wherein the pedestal comprises a second diameter, and wherein the second diameter is less than the first diameter;

a plurality of electrodes disposed proximate the perimeter edge of the disk resonator gyroscope; and

a capacitive gap disposed between the disk resonator gyroscope and each of the plurality of electrodes.

50. The gyroscope of claim 49, wherein the capacitive gap is from between 100nm and 10 μ m.

51. The gyroscope of claim 49, wherein the capacitive gap is from between 100nm and 500nm.

52. The gyroscope of claim 49, wherein at least part of the plurality of electrodes are sense electrodes.

53. The gyroscope of claim 49, wherein the plurality of electrodes are connected to the handle layer by an electrode pedestal.
54. The gyroscope of claim 49, wherein the handle layer comprises a plurality of structures etched into the handle layer.
55. The gyroscope of claim 49, wherein the handle layer comprises a lattice structure having a plurality of unit-cells.
56. The gyroscope of claim 55, wherein the lattice structure is a honeycomb lattice structure having a unit-cell length of from between 10 μ m and 1500 μ m.
57. The gyroscope of claim 49, wherein the disk resonator gyroscope comprises at least one of silicon carbide, aluminum nitride, polycrystalline silicon carbide, polycrystalline silicon, diamond, or fused quartz.
58. The gyroscope of claim 49, wherein the disk resonator gyroscope has a quality factor greater than 2,000,000.

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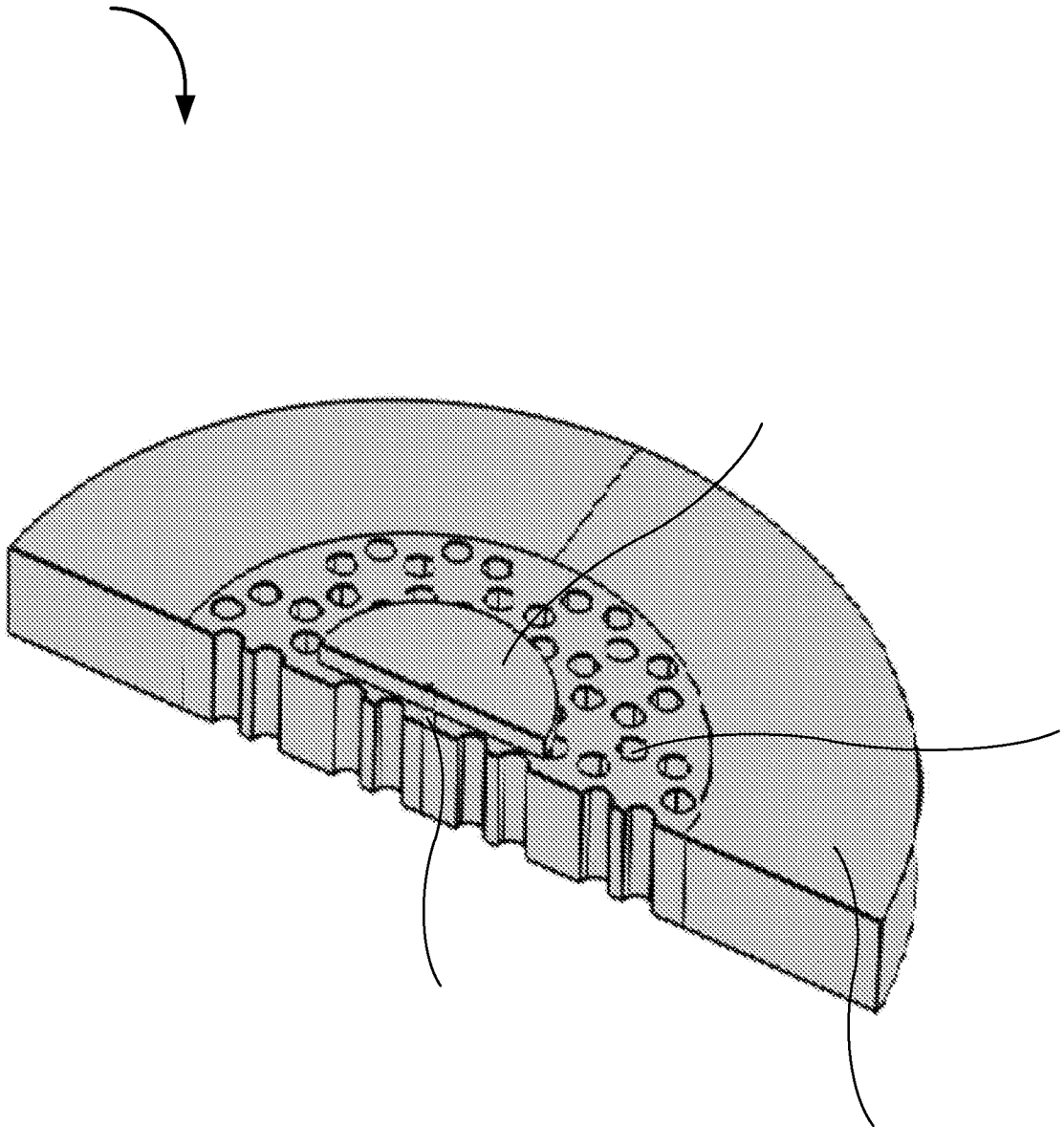


FIG. 1

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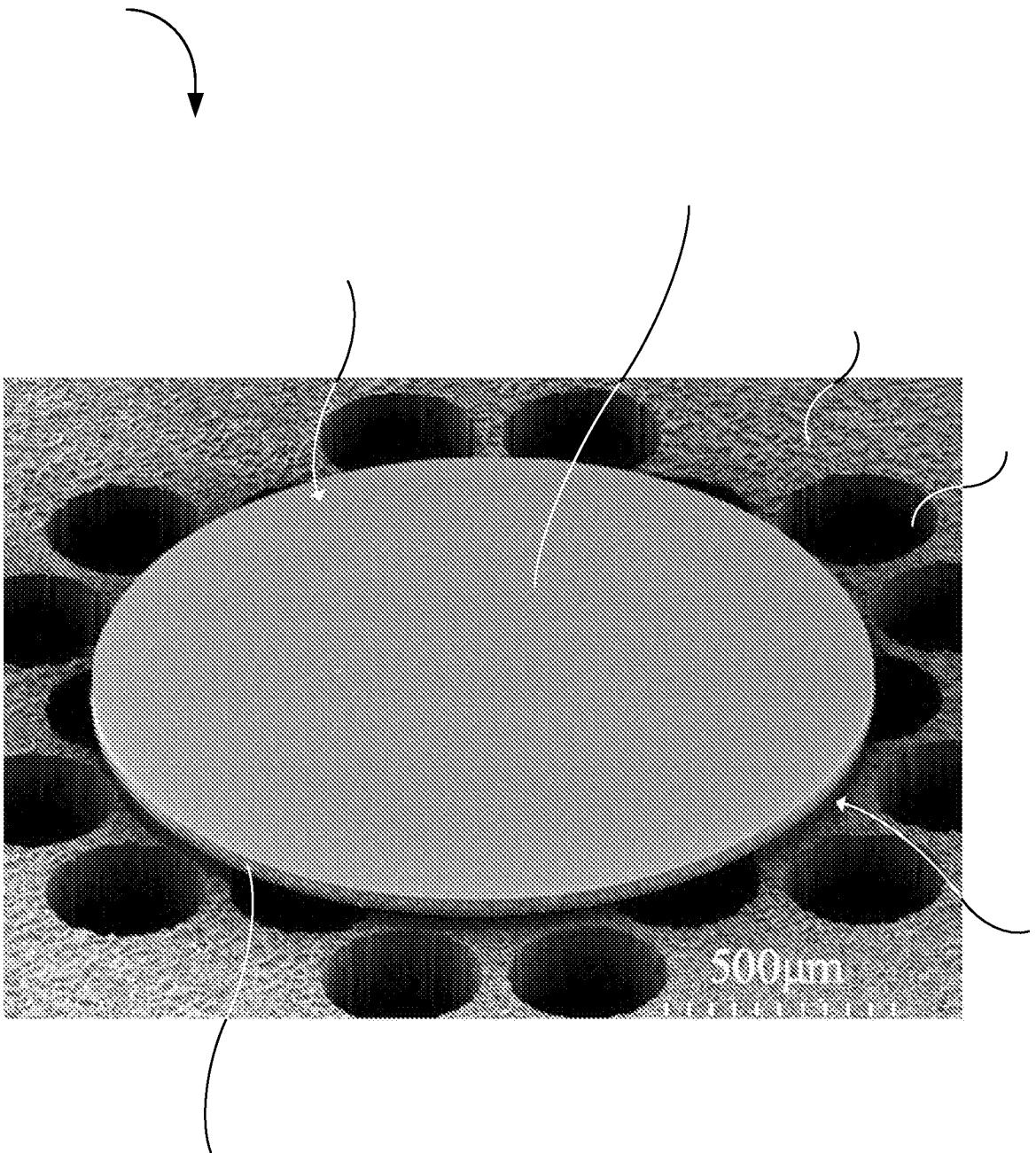


FIG. 2

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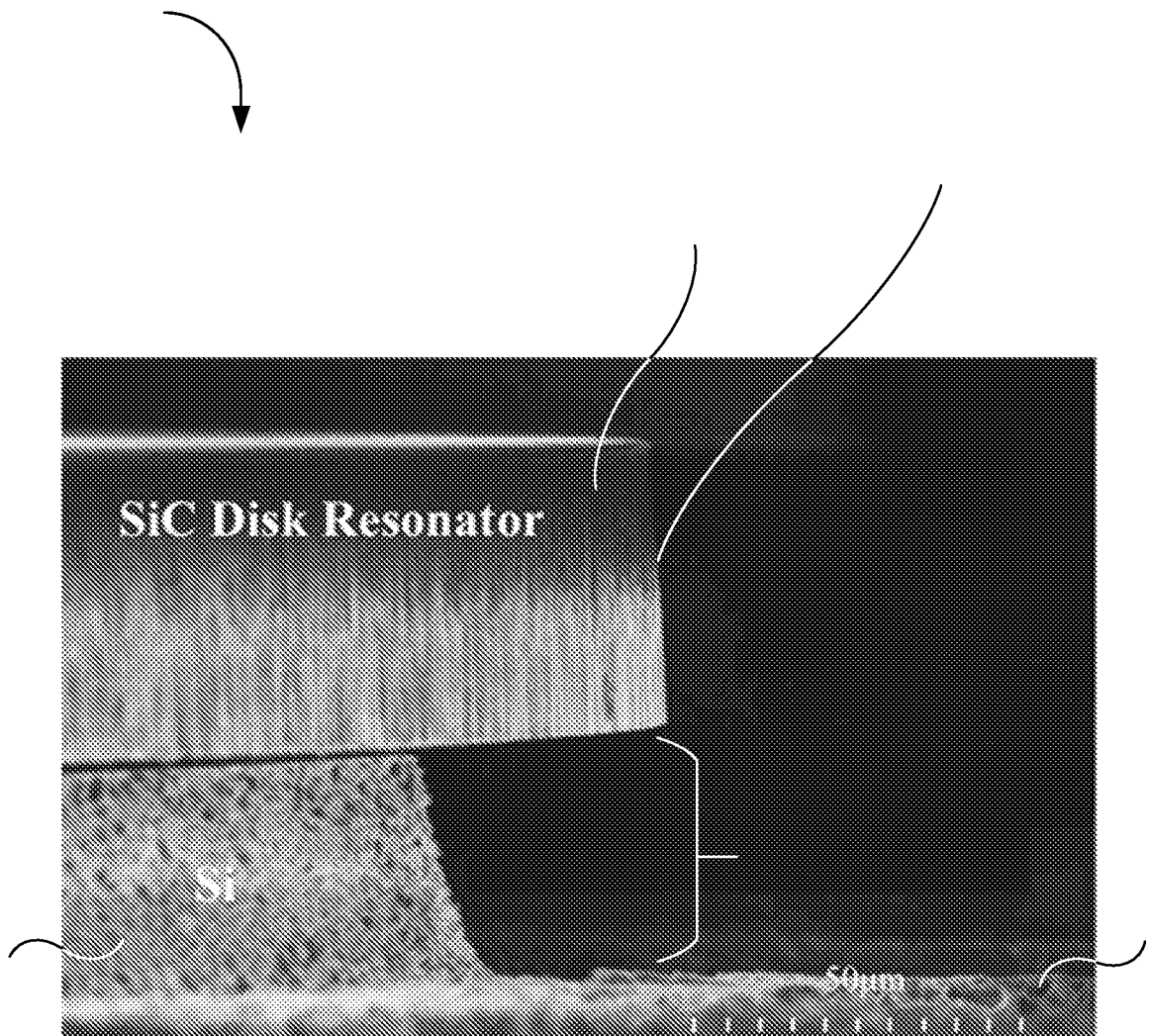


FIG. 3

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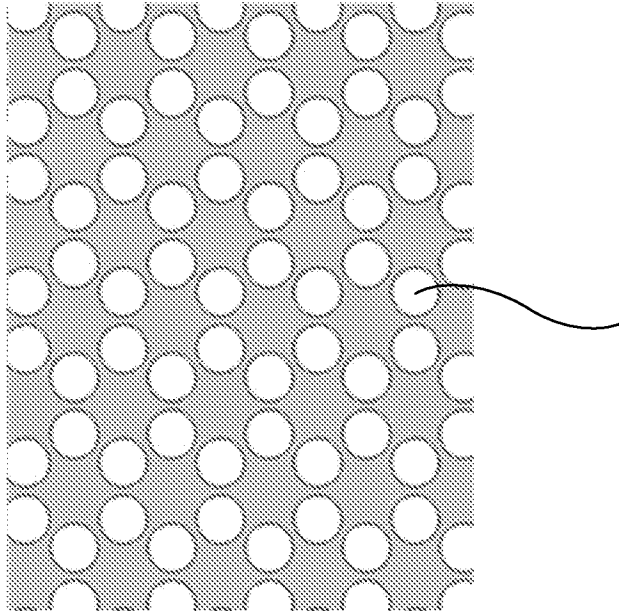


FIG. 4A

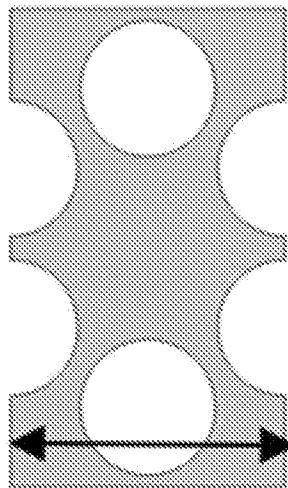


FIG. 4B

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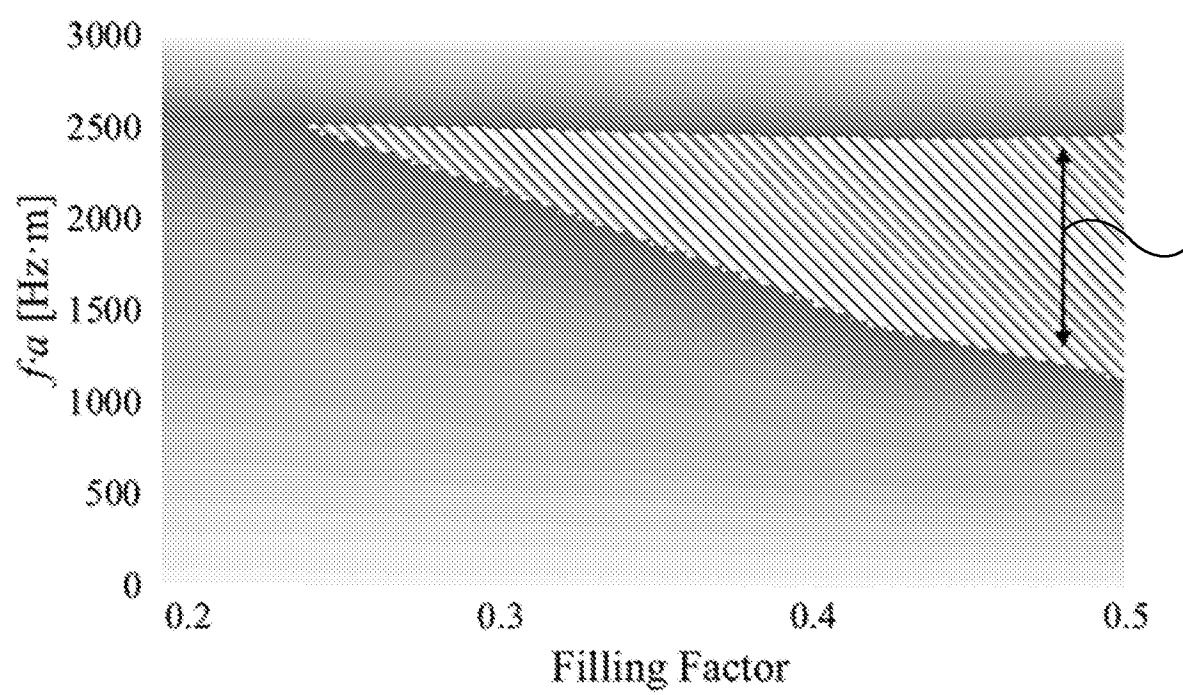


FIG. 5

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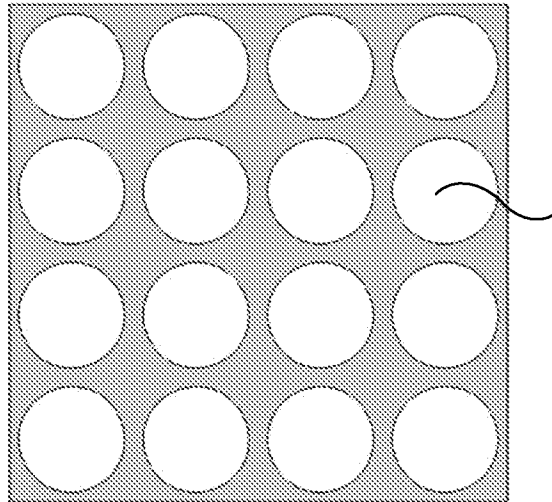


FIG. 6A

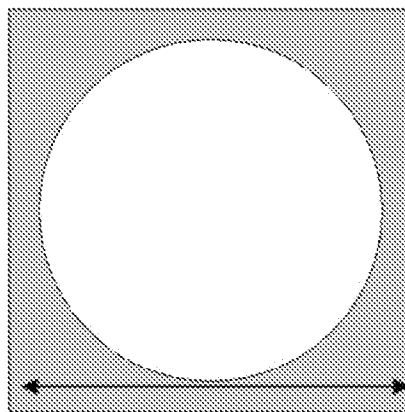


FIG. 6B

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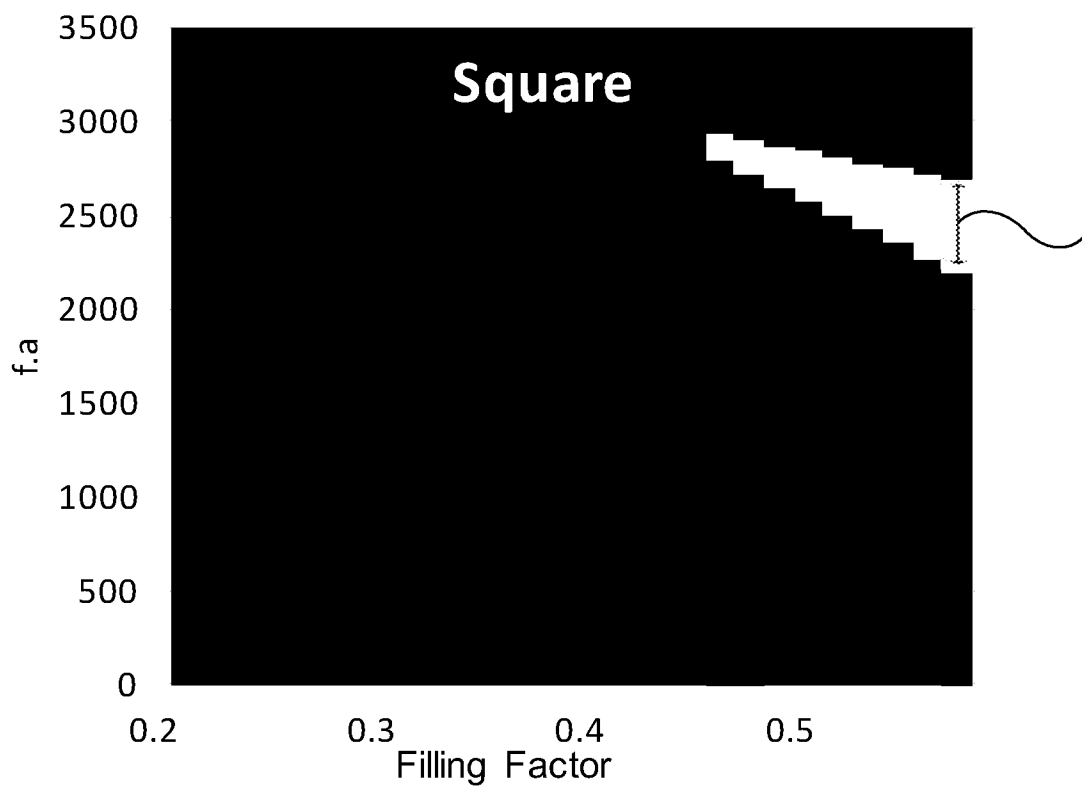


FIG. 7

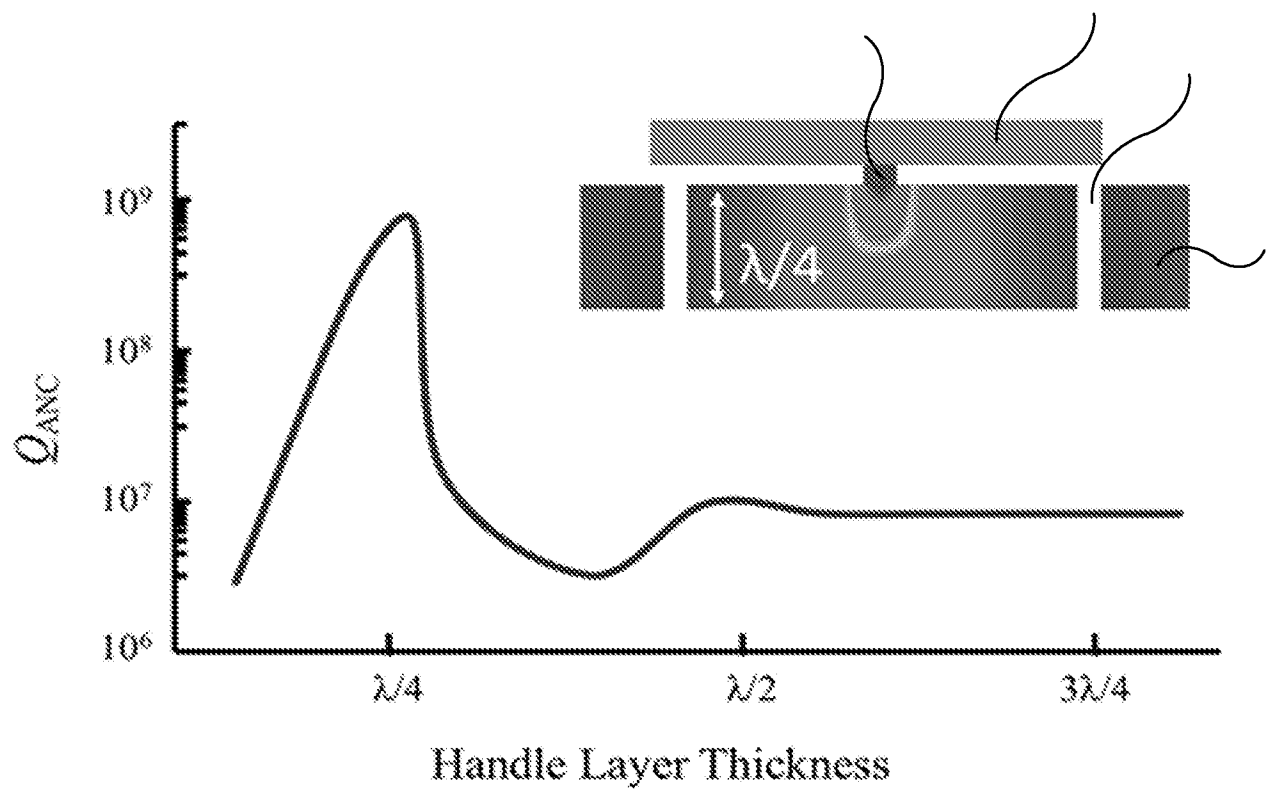


FIG. 8

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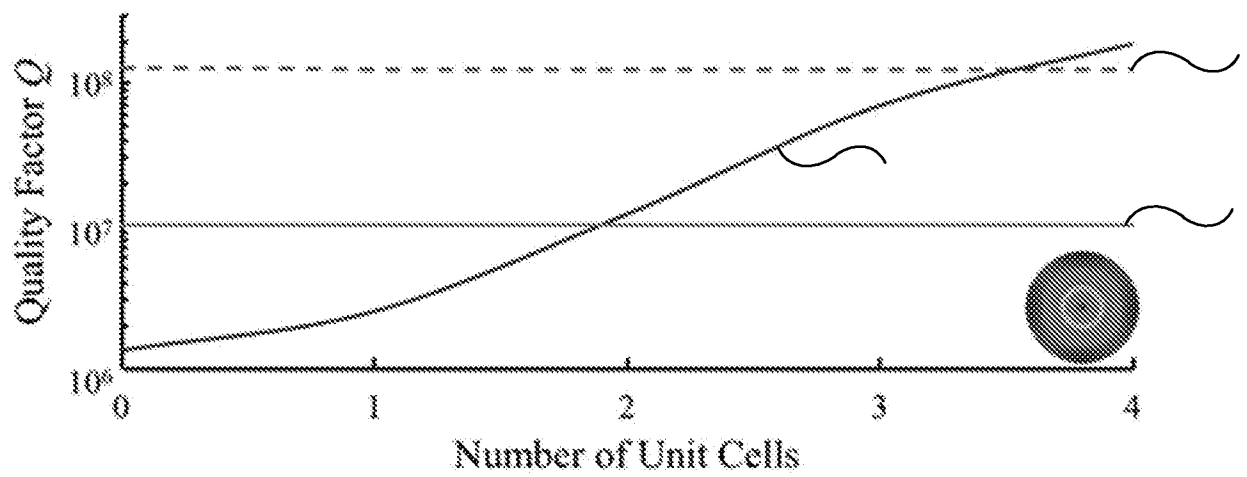


FIG. 9

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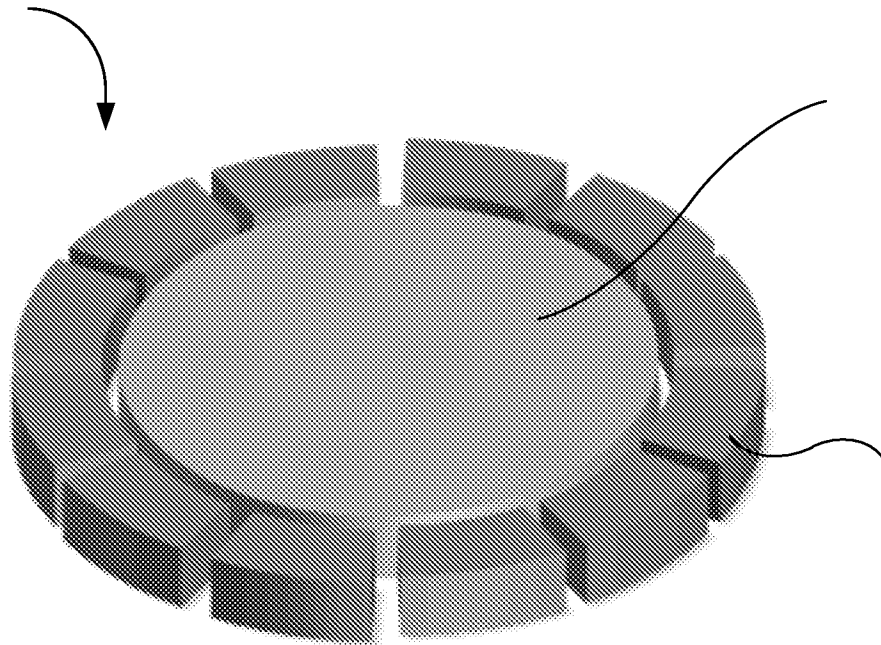


FIG. 10A

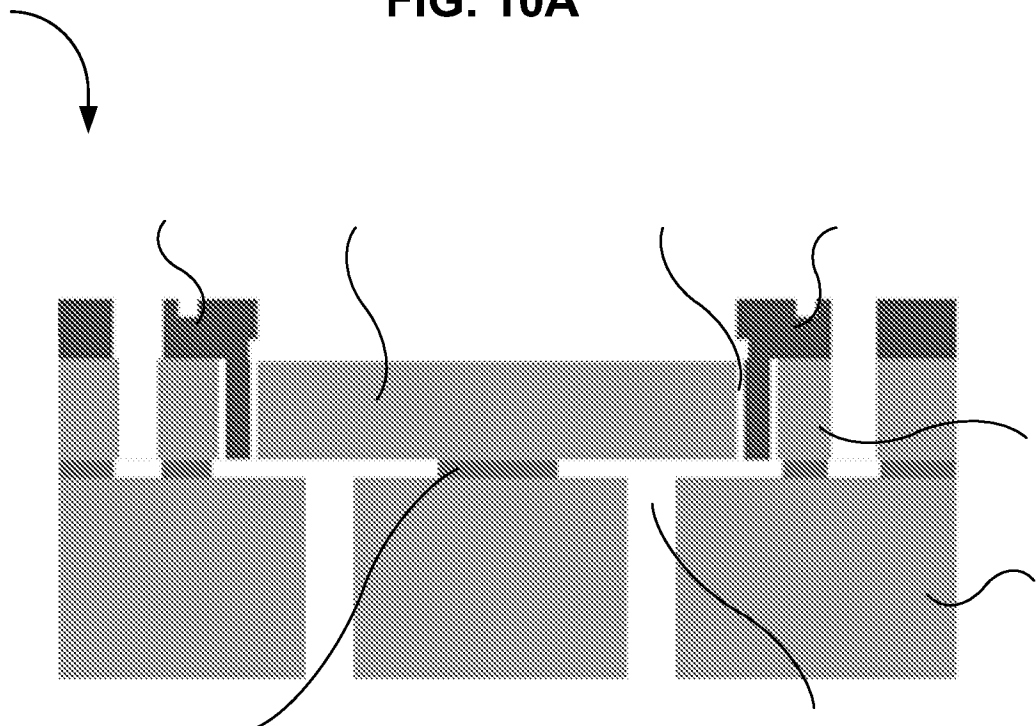


FIG. 10B

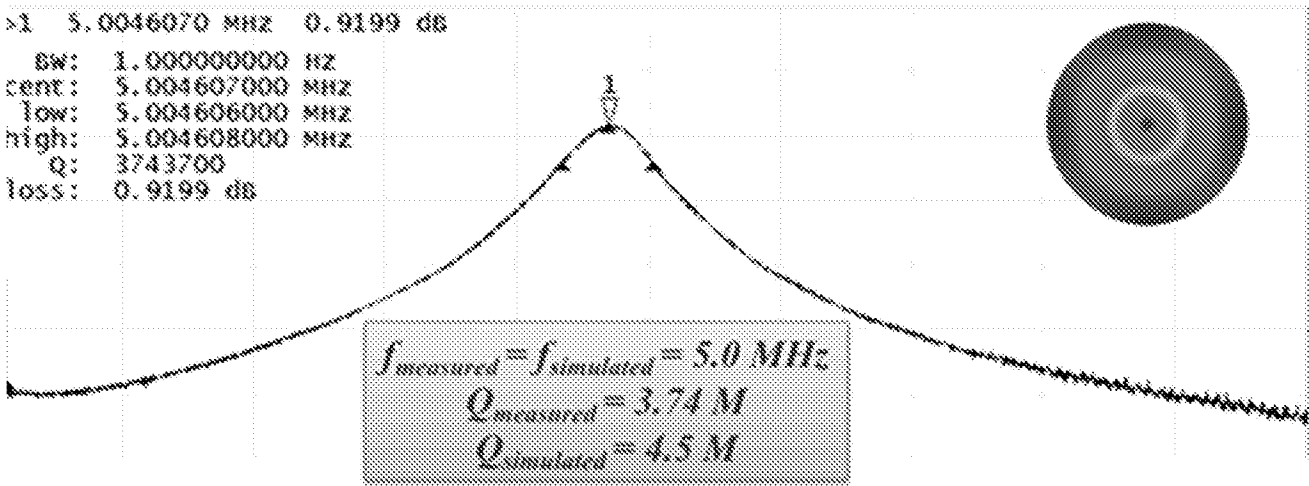


FIG. 11

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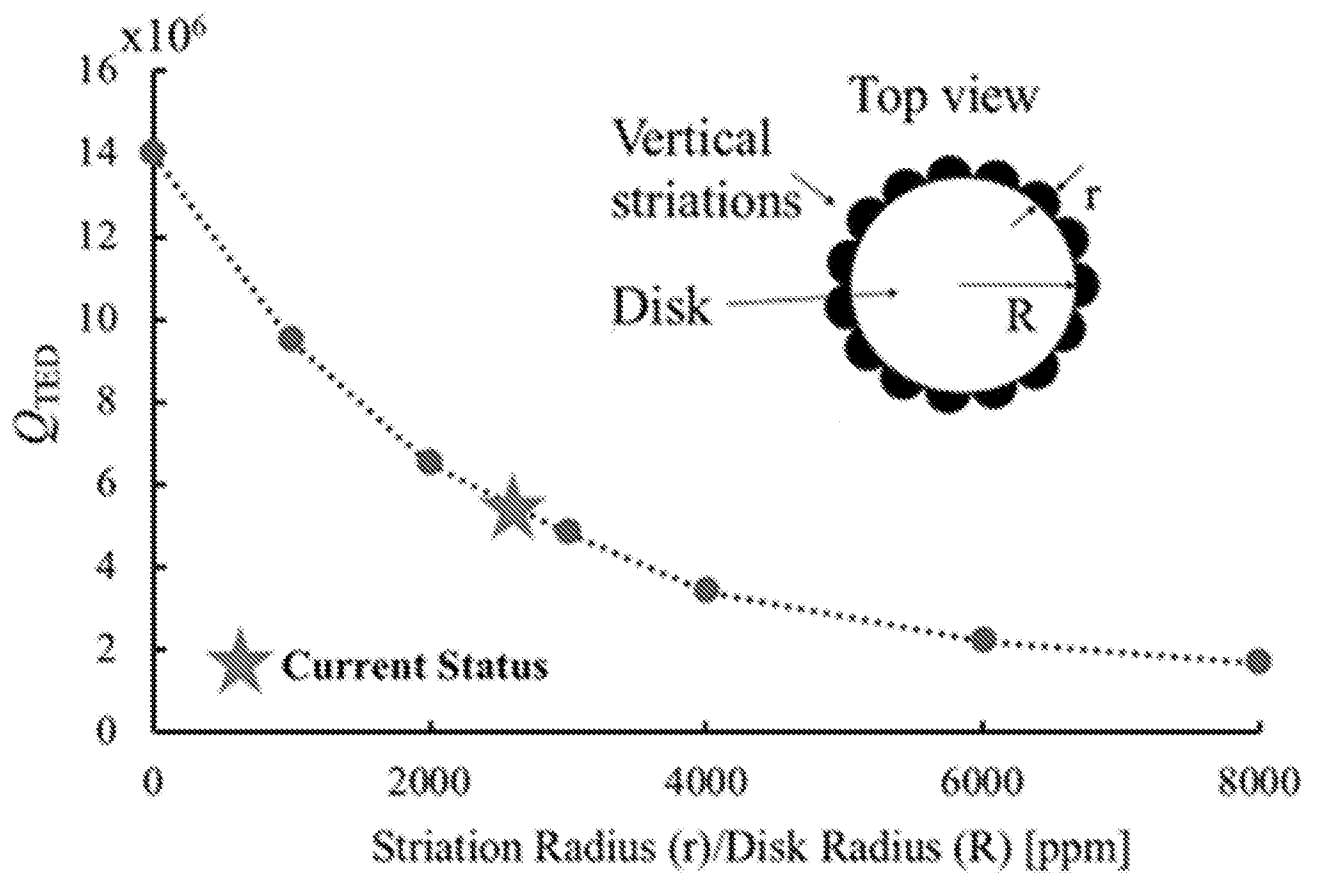


FIG. 12

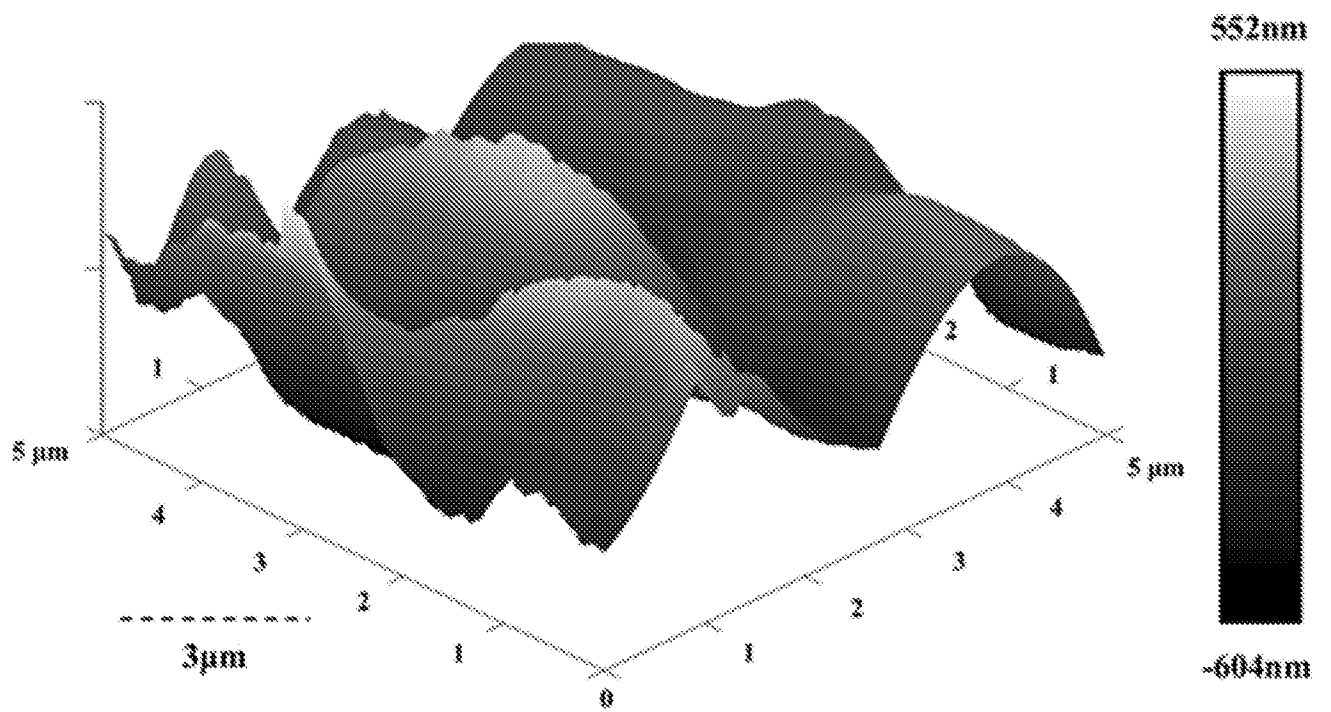


FIG. 13

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 19/20752

A. CLASSIFICATION OF SUBJECT MATTER

IPC - H03H 9/02, 9/17 (2019.01)

CPC - H03H 9/02086, 9/02222, 9/02244, 9/173; G02B 1/005

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

See Search History document

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 --- Y --- A Y --- A A A	US 2016/0211828 A1 (NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY) 21 July 2016 (21.07.2016), FIGS. 1-5, 7, 15; paras [0003], [0053], [0062], [0067], [0074]-[0079], [0086], [0100], [0106] US 2009/0027754 A1 (STEINBERG et al) 29 January 2009 (29.01.2009), para [0021]-[0023], [0107] US 9,634,227 B1 (SAND 9, INC.) 25 April 2017 (25.04.2017), FIGs. 1A, 1B, 3A-3C, col. 3 lns 49-63 US 2007/0119258 A1 (YEE) 31 May 2007 (31.05.2007), paras [0008], [0010], [0041]	1-7, 9-11, 13, 16, 17, 21 ----- 8, 22-30, 33, 34, 37 ----- 12, 14, 15, 18-20, 31, 32, 35, 36, 38-58 ----- 8, 22-30, 33, 34, 37 ----- 31, 32, 35, 36, 38-58 ----- 18-20, 38-58 ----- 31, 32

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

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"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

10 January 2020

Date of mailing of the international search report

27 JAN 2020

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