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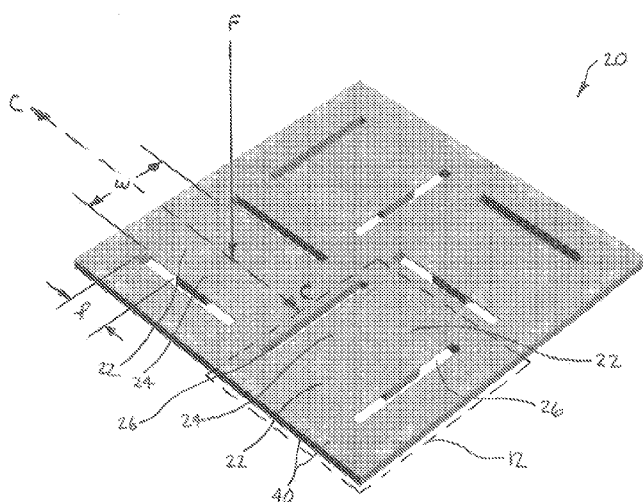
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(54) Title: WIDE-BANDWIDTH MEMS-SCALE PIEZOELECTRIC ENERGY HARVESTING DEVICE

FIG. 1



(57) Abstract: Micro electro-mechanical system (MEMS) devices for harvesting energy are provided. The devices include beams having piezoelectric properties that are anchored on both ends. An external proof mass can be coupled to the beams, and electrodes that are also coupled to the beams can be configured to extract electrical energy from the beams. The external proof mass can help facilitate vibration, which in turn can induce the stretching mode of the beams to dominate. Systems and methods for maintaining an excitation frequency for devices of this nature are also disclosed. The systems and methods can both help start-up the device to begin harvesting energy, as well as maintain the excitation frequency of the device in a high-power output range.

WIDE-BANDWIDTH MEMS-SCALE PIEZOELECTRIC ENERGY HARVESTING DEVICE

5 PRIORITY OF THE INVENTION

The present invention claims priority to U.S. Provisional Application No. 61/282,024, "Wide-Bandwidth MEMS-Scale Piezoelectric Energy Harvester" and filed on December 2, 2009.

10 GOVERNMENT RIGHTS

This invention was made with government support awarded by the Defense Advanced Research Projects Agency under Grant HR0011-06-1-0045, by the National Science Foundation under Grant DMI-0427498, and by the Department of Energy under Award Number DE-FG02-09ER46577. The government has certain rights in the
15 invention.

FIELD

The present invention generally related to energy harvesting devices, and more particularly is directed to a MEMS-scale energy harvesting device that is configured to
20 include piezoelectric components that operate predominantly in a stretching mode.

BACKGROUND

Energy harvesting is the process by which electrical energy is extracted and converted from ambient energy sources. Energy harvesting has existed in one form or
25 another for centuries. Some examples of energy harvesting devices include watermills, windmills, turbines, hydroelectric dams, and solar power systems. The most mature energy harvesting devices are typically very large; they harvest energy on a macro-scale.

More recently, work has been done to create micro-scale energy harvesting devices. The goal is to create small devices that can output significant amounts of
30 electrical power in comparison to their size. Attempts have been made on a micro-scale to create microwatts to milliwatts of electrical power from solar, vibration, thermal, electromagnetic, and biological sources. For instance, vibration energy harvesting methods include using electromagnetic induction, electrostatic generation, and

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piezoelectric materials to harvest energy. When using piezoelectric materials, the energy harvesting devices directly convert applied strain energy into usable electric energy. Present designs of piezoelectric energy devices typically have a high-Q linear cantilever beam that resonates at small environmental vibrations and results in sizable bending strain on a piezoelectric layer of the beam to generate electrical charge. While piezoelectric energy harvesting devices can be used in micro electro-mechanical systems (MEMS), the present designs are limited.

For instance, harvested power decays sharply if the input vibration frequency is off more than one or two percent from the natural frequency of the beam structure. The higher the Q-factor, the less robust the system becomes. Further, the density of the actual harvested power is orders of magnitude less than the maximum power density that can be theoretically extracted from such devices. The inventors discovered that this is because the bending of a cantilever beam cannot generate uniform and large enough strain values to even come close to approaching the theoretical maximum power density. In addition to low power density output, these devices suffer from a narrow frequency bandwidth, *i.e.*, there is only a small spectrum of frequencies that produce “useable” power. While various passive and active frequency-tuning mechanisms have been reported, the reality is that prior to the inventors, nobody provided a practical solution to make piezoelectric energy harvesting devices efficient.

While progress continues to be made to allow electric power to be generated by MEMS-scale energy harvesting devices that is adequate, or even superior, to power components such as ultra-low-power (ULP) circuits and wireless sensors, there is still room for improvement. In particular, it is desirable to create MEMS-scale piezoelectric energy harvesting devices that produce wider frequency bandwidth and higher power densities—bandwidths and densities that better approach the theoretical maximums for such devices.

SUMMARY

Systems, devices, and methods are provided for harvesting energy. The systems, devices, and methods are primarily directed to micro electro-mechanical systems (MEMS) that rely on piezoelectric properties to extract energy, which in turn can be converted to power. In one exemplary embodiment a MEMS device for harvesting

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energy includes at least one piezoelectric beam that is fixedly anchored at both a first end and a second end and the beam has a length dimension in a direction between the first and second ends. At the first end the beam can be anchored to a substrate and at the second end the beam can be anchored to a proof mass platform. The beam can be configured such that external vibration induces stretching of the beam in its length dimension. The device can also include a pair of electrodes that are electrically coupled to the beam. The pair of electrodes can be configured to extract electrical energy from the beam. An external proof mass can also be part of the device. In one embodiment the external proof mass is coupled to the proof mass platform.

A stiffness of the beam can be substantially nonlinear. In one embodiment, the device includes one or more piezoelectric layers disposed on the beam. A number of different dimensions can define the beam. For example, a length of the beam can be about 100 millimeters or less. By way of further example, the beam can exhibit a ratio of thickness-to-deflection in a range of about 0.01 to about 1. Still further, a deflection-to-length ratio of the beam can be at least greater than a square root of a residual stress-to-Young's modulus ratio. In one embodiment, the device can be configured to generate a power density greater than or equal to about 1 Watt per cm³ in response to an external vibration.

The external proof mass can be at least about 50 milligrams. Further, the external proof mass can be removably and replaceably coupled to the piezoelectric beam. In one embodiment, the electrodes are interdigitated in a direction perpendicular to strain induced in the beam during vibration. A force vector applied by the proof mass can be substantially perpendicular to the length of the beam and the device can be configured such that a centerline extending from the beam in its length dimension intersects the proof mass force vector.

In another embodiment of a MEMS device for harvesting energy, the device can include a plurality of piezoelectric beams, a pair of electrodes electrically coupled to each beam, and an external proof mass. The beams can be fixedly anchored at both a first end and a second end, and the beams can have a length, width, and thickness configured such that external vibration induces stretching in the length dimension of the beam. The length of beam can extend between the anchored first and second ends. In one embodiment, the first end is fixedly anchored to a substrate and the second end is

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fixedly anchored to a proof mass platform. The pair of electrodes can be configured to extract electrical energy from the beam. In one embodiment, the external proof mass is coupled to the proof mass platform.

5 A stiffness of the beams can be substantially nonlinear. In one embodiment, the device includes one or more piezoelectric layers disposed on the beams. A number of different dimensions can define the beams. For example, a length of the beams can be about 100 millimeters or less. By way of further example, the beams can exhibit a ratio of thickness-to-deflection in a range of about 0.01 to about 1. Still further, a deflection-
10 to-length ratio of the beams can be at least greater than a square root of a residual stress-to-Young's modulus ratio. In one embodiment, the device can be configured to generate a power density greater than or equal to about 1 Watt per cm^3 in response to an external vibration.

 The external proof mass can be at least about 50 milligrams. Further, the
15 external proof mass can be removably and replaceably coupled to the piezoelectric beams. In one embodiment, the electrodes are interdigitated in a direction perpendicular to strain induced in the beams during vibration. A force vector applied by the proof mass can be substantially perpendicular to the length of one of the beams and the device can be configured such that a centerline extending from one of the beams in its length
20 dimension intersects the proof mass force vector.

 In one embodiment of a MEMS device assembly for harvesting energy, the device includes two or more MEMS devices for harvesting energy, such as the devices discussed above. The devices can be constructed on a common substrate, and further, the devices can share a common proof mass. The common proof mass can induce
25 substantially synchronized vibration of the beams of the devices, and further, can reduce phase differences in power generation. In one embodiment the devices are arranged in a non-parallel configuration. In another embodiment, the beam length dimension of one device can be substantially perpendicular to the beam length dimension of another of the devices. The assembly can also include multiple proof mass receiving platforms. The
30 proof mass receiving platforms can each include a coupling feature for coupling to the common external proof mass. In one embodiment, the plurality of devices of the assembly can be disposed in four quadrants that are equally disposed from a center of

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the assembly and the proof mass receiving platforms can be disposed centrally within each quadrant.

5 In yet another embodiment of a MEMS device for harvesting energy, the device includes at least one piezoelectric beam fixedly anchored a first end of the beam and a second end of the beam and a pair of electrodes electrically coupled to the beam. The beam can be anchored at the first end to a substrate and at the second end to a proof mass. The beam can be configured such that external vibration induces stretching of the beam in its length dimension. The length dimension can be defined by the dimension
10 extending between the first and second ends. The pair of electrodes can be configured to extract electrical energy from the beam. The device itself can be configured to generate a power density greater than or equal to about 1 Watt per cm³ in response to external vibration.

15 In an embodiment of a resonating device for harvesting energy, the device can include at least one piezoelectric beam fixedly anchored at first and second ends thereof and a pair of electrodes electrically coupled to the beam. The electrodes can be configured to extract electrical energy from the beam. The device itself can be configured such that the electrical energy extracted by the pair of electrodes is greater than the mechanical damping that can be extracted.

20 In an exemplary method for harvesting energy, the method includes detecting an amplitude of vibration of an energy harvesting device having a piezoelectric component and a proof mass and activating a control unit to exploit an actuation mode of the piezoelectric component of the energy harvesting device. Activating the control unit activates a bending moment that is substantially synchronized with a motion of the proof
25 mass. In one embodiment, the amplitude and frequency of vibration of the energy harvesting device can achieve a high-energy stable region in less than one second. The method can also include detecting an approach of a maximum stabilization point and disabling actuation to prevent the frequency from exceeding the maximum stabilization point. Further, the method can include detecting an approach of a minimum stabilization
30 point and enabling actuation to prevent the frequency from falling below the minimum stabilization point.

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BRIEF DESCRIPTION OF DRAWINGS

This invention will be more fully understood from the following detailed description taken in conjunction with the accompanying drawings, in which:

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FIG. 1 is a perspective view of one exemplary embodiment of an energy harvesting device;

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FIG. 2 is a perspective view of one exemplary embodiment of a proof mass for coupling to the energy harvesting device of FIG. 1;

FIG. 3 is a semi-transparent perspective view of the proof mass of FIG. 2 coupled to the energy harvesting device of FIG. 1;

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FIG. 4 is a schematic view of the electrode configuration of the energy harvesting device of FIG. 1;

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FIG. 5A is a schematic cross-section view of an energy harvesting device illustrating one step of a fabrication process for creating the device, the step being the formation of a structural layer around an internal proof mass;

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FIG. 5B is a schematic cross-section view of an energy harvesting device illustrating another step of a fabrication process for creating the device, the step being the formation of an active layer on top of the structural layer of FIG. 5A;

FIG. 5C is a schematic cross-section view of an energy harvesting device illustrating another step of a fabrication process for creating the device, the step being the formation of interdigitated electrodes on top of the active layer of FIG. 5B;

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FIG. 5D is a schematic cross-section view of an energy harvesting device illustrating another step of a fabrication process for creating the device, the step being the formation of a passivation layer on top of the active layer and the interdigitated electrodes of FIG. 5C;

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FIG. 5E is a schematic cross-section view of an energy harvesting device illustrating another step of a fabrication process for creating the device, the step being patterning the passivation layer of FIG. 5D;

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FIG. 5F is a schematic cross-section view of an energy harvesting device illustrating another step of a fabrication process for creating the device, the step being patterning a top side of the structural layer of FIG. 5E;

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FIG. 5G is a schematic cross-section view of an energy harvesting device illustrating another step of a fabrication process for creating the device, the step being patterning a back side of the structural layer of FIG. 5F;

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FIG. 5H is a schematic cross-section view of an energy harvesting device illustrating another step of a fabrication process for creating the device, the step being patterning the internal proof mass of FIG. 5G;

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FIG. 5I is a schematic cross-section view of an energy harvesting device illustrating coupling the energy harvesting device of FIG. 5H to a base and coupling an external proof mass to the energy harvesting device of FIG. 5H;

FIG. 6 is a perspective view of another exemplary embodiment of an energy harvesting device;

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FIG. 7 is a perspective view of the energy harvesting device of FIG. 6 with an external proof mass separated from a substrate;

FIG. 8 is a perspective view of the substrate of the device of FIG. 7 and having electrodes removed therefrom;

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FIG. 9 is a perspective view of the external proof mass of the device of FIG. 7;

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FIG. 10 is a graph illustrating the possible deflections of an energy harvesting device with respect to its excitation frequency in accordance with the present invention;

5 FIG. 11 is a graph illustrating the voltage that results from the bending that occurs in the energy harvesting device associated with the graph of FIG. 10 with respect to the excitation frequency of the device;

10 FIG. 12 is a graph illustrating the voltage that results from the stretching that occurs in the energy harvesting device associated with the graph of FIG. 10 with respect to twice the excitation frequency of the device;

15 FIG. 13 is graph illustrating the normalized power density of an energy harvesting device in accordance with the present invention having an external proof mass and having no external proof mass as compared to the normalized power density of other energy harvesting devices as identified in a study by Khalil Najafi of the University of Michigan;

20 FIG. 14 is a block diagram of a start-up circuit for use with an energy harvesting device, such as the energy harvesting device of the present invention;

FIG. 15 is a graph illustrating the amplitude of an energy harvesting device over a normalized period of time in which the start-up circuit of FIG. 14 is not employed; and

25 FIG. 16 is a graph illustrating the amplitude of an energy harvesting device over a normalized period of time in which the start-up circuit of FIG. 14 is employed.

DETAILED DESCRIPTION

30 Certain exemplary embodiments will now be described to provide an overall understanding of the principles of the structure, function, manufacture, and use of the devices and methods disclosed herein. One or more examples of these embodiments are illustrated in the accompanying drawings. Those skilled in the art will understand that the devices and methods specifically described herein and illustrated in the

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accompanying drawings are non-limiting exemplary embodiments and that the scope of the present invention is defined solely by the claims. The features illustrated or described in connection with one exemplary embodiment may be combined with the features of other embodiments. Such modifications and variations are intended to be included within the scope of the present invention.

In one exemplary embodiment of an energy harvesting device, the device uses a micro electro-mechanical system (MEMS) for harvesting energy. More particularly, the device includes one or more beams that are configured to have piezoelectric properties and that are fixedly anchored at both ends. For instance, one end of the beam(s) can be anchored by a substrate while another end of the beam(s) can be anchored by a platform for receiving an external proof mass. The length of the beam(s) is the portion extending between the two anchored ends. The beam(s) can be anchored such that external vibrations induce stretching of the beam(s) in its length dimension. Further, electrodes can be coupled to the beam(s) such that the electrodes can extract electrical energy from the beam(s), such as the electrical energy that results from the induced stretching of the beam(s). One way by which external vibrations can be facilitated is by way of an external proof mass that is coupled to the beam(s).

As illustrated by FIGS. 1-4, the aforementioned design can be replicated in a larger structure that includes multiple beams configured in a similar manner to form an energy harvesting device 10 (FIG. 3). As shown in FIG. 1, a substrate 20 is provided that is configured to include a plurality of beams 22, a plurality of proof mass platforms 24, and a plurality of electrode pairs 40. The beams 22 are anchored at both ends. A length l of the beams 22 extends between the two anchored ends, as illustrated in FIG. 1. One of the electrode pairs 40 is electrically coupled to each end of each beam 22 of the device 10. An external proof mass 30, illustrated by FIG. 2, can be configured to be received by the substrate 20, and more particularly by the proof mass platforms 24. By coupling the external proof mass 30 to the proof mass platforms 24, the external proof mass 30 also is coupled to the beams 22. When combined, as illustrated by FIG. 3, the substrate 20 and the external proof mass 30 form the energy harvesting device 10. The resulting device 10 allows the vibration phase of each beam 22 to be substantially synchronized with the other beams. Further, the resulting device 10 is configured in a manner that strains resulting from the stretching mode of the beams 22 dominate

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movement created by an external vibration caused by the external proof mass 30. As shown in FIGS. 1 and 3, a force vector F applied by the external proof mass 30 to the substrate 20 can be substantially perpendicular to a length l of any one of the beams 22 of the device 10. Additionally, a centerline C that extends from any one of the beams 22 in its length dimension can intersect the force vector F that is applied by the external proof mass 30.

In embodiments in which there is no external proof mass, the substrate 20 and its associated components, such as the beams 22 and the electrode pairs 40, can form an energy harvesting device. Still further, one or more beams 22 that are anchored at both ends, with or without an external proof mass, can form an energy harvesting device. These alternative energy harvesting devices also operate in a manner similar to the device 10, that is movement caused by an external vibration, whether the vibration is caused by an external proof mass or not, can result in a dominant stretching mode of the beam(s), and thus the strains that result from the dominant stretching mode create the dominant electrical output.

By clamping the beams 22 at both ends, lateral and rotational motion of the beams 22 are negligible and vertical motion caused by an external vibration, such as vibration caused by the external proof mass 30, causes a strong stretching force to be applied to the beams 22 to compensate for the inevitable length increase of the beam. This large deflection results in two kinds of strain: a bending strain, S_B , and a stretching strain, S_S . The bending strain is not uniform and typically varies along the length l of the beam 22 and across a thickness of the beam 22 with opposite signs in upward and downward motion. The stretching strain, on the other hand, is always tensile and is typically uniform across the length l of the beam 22 and the thickness of the beam 22 for both upward and downward motion. The stiffness that results from the stretching strain is substantially nonlinear.

The load-deflection characteristics of the doubly-clamped beam can be modeled as an amplitude-stiffened Duffing spring. The elastic force can be divided into two parts: (1) a linear term that is the result of the small deflection bending of the beam 22 and the residual stress in the beam 22; and (2) a nonlinear term that results from the stretching of the beam 22. In one exemplary embodiment, a thickness of the beam is

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sufficiently thin that the effects of the linear term are negligible, and thus can be neglected.

5 The wide-bandwidth resonance that results from this configuration can be explained by the negative feedback that results from Duffing stiffening. Stretching stiffness—the dominant stiffness in the inventive configurations due to the stretching force contributing as the dominant restoring force on the device 10—induces a nonlinear stiffness, k_{eq} , that is amplitude-dependent in accordance with the following equation:

$$10 \quad k_{eq} = (k_B + k_\sigma) + \frac{3k_S Z^2}{4} \quad (\text{Eq. 1}),$$

where k_B is the bending stiffness, k_σ is the stiffness due to the residual stress, k_S is the stretching-based stiffness, and Z is the amplitude of deflection. The resulting nonlinear stiffness forces the equivalent resonance frequency to track the excitation frequency.

15 Thus, to achieve a stronger nonlinearity, which in turn provides for a wider resonance bandwidth, the equivalent stiffness is mainly controlled by the nonlinear stiffness term such that:

$$20 \quad k_B + k_\sigma \ll k_S Z^2 \quad (\text{Eq. 2}).$$

Although in a MEMS-scale resonator or energy harvesting device the average stiffness due to residual stress can be substantial, the design of the present energy harvesting devices minimizes the effects in a number of ways, for instance, by optimizing beam dimensions, choosing materials that minimize the average residual stress, and

25 incorporating a heavy external proof mass.

As shown in FIG. 1, the substrate 20 includes eight beams 22. Each combination of beams 22, electrode pairs 40, and portions of substrate 20 adjacent to a single proof mass platform 24 can be considered a single device 12, thus, in the illustrated embodiment, there are four devices 12. Each of the four devices 12 are disposed in a

30 different quadrant of the device 10, and each device 12 is equally disposed from a center of the device 10. Likewise, as illustrated, the proof mass platforms 24 are disposed centrally within each quadrant. Such a configuration allows for beam stretching forces

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to be maximized. As shown, the devices 12 are arranged such that two of the devices 12 face in one direction and two of the devices 12 face in a different direction that is substantially perpendicular to the direction of first devices 12. More particularly, a
5 beam length dimension of one device 12 can be substantially perpendicular to a beam length dimension of another device 12. The devices 12, and thus the beams 22, can face in any direction, including all in the same direction.

The beams 22 are anchored at one end by the substrate 20 and at the other end by one of the proof mass platforms 24. The length l of the beams 22 is defined by the
10 portion disposed between these two ends, while a width w of the beams 22 is defined by the portion extending between the two troughs 26 of the device 12. The troughs 26, which can be formed in the substrate 20, help facilitate bending of the beams 22. The beams serve as a structural membrane upon which piezoelectric layers can be deposited, or alternatively, can be made of piezoelectric materials. In an alternative embodiment,
15 each beam 22 can be two or more separate beams, thus creating at least sixteen beams, and the beams can be anchored either by the substrate 20 on both ends of the beam or by the substrate 20 on one end of the beam and one of the proof mass platforms 24 on the other end of the beam, depending on whether the beam is adjacent to one of the proof mass platforms 24. In yet another alternative embodiment, the beams 22 on either side
20 of one of the proof mass platforms 24 can form a single beam that is anchored at both ends by the substrate 20 and an external proof mass can be coupled to the substrate 20 in any number of ways. For example, if proof mass platforms 24 were included the platforms 24 could be coupled to the beams 22 in a manner that still allowed an external proof mass to induce a dominant stretching force on the beams 22. Other configurations
25 that take advantage of the double-anchored beams with an external proof mass can likewise be created without departing from the spirit of the invention.

The beams 22 can be made of a number of materials that are capable of stretching. Some examples of materials that can be used to form the beams 22 include crystals, ceramics, metals, silicon, and polymers. Many of these materials, such as
30 crystals and ceramics, can have naturally occurring piezoelectric properties. Regardless, the beams 22 can be configured to have piezoelectric properties, whether by the use of materials having such properties or by incorporating such materials into or onto the beams 22. Examples of piezoelectric materials that can be used to form the beams 22, or

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to be used as part of one or more layers disposed on the beams 22, include langasite, barium titanate, aluminum nitride, zinc oxide, and lead zirconate titanate, which is commonly known as PZT.

5 The beams 22 can have a wide variety of shapes and dimensions, depending at least in part on the desired effects of the system, the size and capabilities of the components with which they will be used, and the desired resonance bandwidth and power output. In the illustrated embodiment the beams 22 are generally rectangular, although in other embodiments they can be generally square, generally elliptical,
10 generally triangular, generally trapezoidal, or a variety of other shapes. All of the beams do not have to have the shape, although in one exemplary embodiment they do each generally have the same shape. For MEMS-scale use, it can be preferable for the width w of the beams 22 to not exceed approximately 100 millimeters, and it can be further preferable for the lengths l of the beams 22 to not exceed approximately 10 millimeters.
15 In certain embodiments the length l of the beams 22 can be in the range of about 0.1 millimeters to about 10 millimeters. In one particular embodiment the length l of the beams 22 can be about 3 millimeters. When described with respect to deflection and residual stress, a deflection-to-length ratio can be at least greater than a square root of a residual stress-to-Young's modulus ratio.

20 While in the illustrated embodiment a length l of each beam 22 is approximately the same and a width w of each beam 22 is approximately the same, along the width w is larger than the length l , in other embodiments the beams 22 can have different lengths and/or widths. Further, while in the illustrated embodiment the lengths l and widths w of the beams 22 extend approximately in the same direction, but lengths l and widths w of
25 an adjacent group of two beams in an adjacent device extend in a direction that is approximately perpendicular to a length l and width w of the beams 22 of the first device 12, other beam configurations can also be used. For instance, the lengths l and widths w of all of the beams 22 can extend in the same direction, or alternatively, the lengths l and widths w of adjacent beams 22 in the same device 12 can extend in different directions.
30 However, it is generally preferable for the resulting configuration to be approximately symmetrical for the device 10 to prevent non-stretching based forces and strains from affecting the output of the system.

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The beams 22 can also have a variety of thicknesses, although the beams can generally be described as thin. In one embodiment the beam has a thickness in the range of about 0.001 millimeters to about 0.5 millimeters. In one particular embodiment the thickness of the beam is about 0.3 millimeters. When described with respect to the deflection of beams 22, a ratio of thickness-to-deflection can be in a range of about 0.01 to about 1. The thickness of the beams 22 can be just the beam itself, or alternatively, can include the materials, such as one or more piezoelectric layers, disposed thereon.

Similar to the beams 22, the electrode pairs 40 can have a variety of configurations. In the illustrated embodiment, each electrode pair 40 is coupled to the beam 22 and terminated in contact pads on the substrate in a manner that allows the electrode pairs 40 to extract electrical energy from the beam 22. In particular, as illustrated in FIG. 4, the electrode pairs 40 are interdigitated in a direction perpendicular to strain that is induced in the beam by way of an external vibration. While there are eight beams in the illustrated embodiment, each beam 22 has two electronic circuits, each circuit covering roughly half of the beam length. Thus, as shown, there are a total of sixteen circuits and sixteen electrode pairs 40.

As shown in FIGS. 1, 3, and 4, the electrode pairs 40 are disposed around a perimeter of the substrate 20 and then at the anchored ends of the beams 22, but in other embodiments the electrode pairs 40 can be disposed in other locations on the device 10. FIG. 4 schematically illustrates the electrode pairs 40. Using separate electrode pairs 40 on each end of the beam 22 makes it easier to access the bending mode for measurement, harvest energy at low-amplitude vibration, and access an actuation mode that is used as a part of a start-up circuit, which is discussed in greater detail below with respect to FIGS. 14-16.

The electrode pairs 40 can be wired in series, parallel, or a mixed combination of series and parallel, but in the illustrated embodiment the electrode pairs 40 are wired in parallel. As a result, because a multitude of electrode pairs 40 are provided, even if one electrode pair 40 has complications, the other electrode pairs 40 can continue to extract electrical energy from the beams 22. Further, although in the illustrated embodiment the electrodes are all described as being electrode pairs, any number of electrodes can be used, including a single electrode for each beam or more than one or two pairs of electrodes per beam.

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The substrate 20 on which the electrode pairs 40 can be disposed can be made of a variety of materials. For example, the substrate 20 can be made of a semiconductive material, such as silicon. The substrate 20 can also have a number of shapes and sizes, but in a MEMS-scale system, preferably the substrate 20 is no larger than a United States quarter. In other embodiments the substrate can have a length or width in the range of about 1 millimeter to about 30 millimeters, and more particularly in the range of about 2 millimeters to about 20 millimeters. As shown, the substrate is generally square in nature, but in other embodiments it can be generally rectangular, generally elliptical, generally circular, or any other number of shapes. Further, the substrate 20 can have a variety of thicknesses. For instance, it can have a thickness in the range of about 0.01 millimeters to about 2 millimeters, and more preferably in the range of about 0.5 millimeters to about 1 millimeter.

Cavities can be formed in the substrate to receive beams 22 so the substrate 20 can anchor at least one end of the beams 22. The substrate 20 can also anchor one or both ends of the proof mass platforms 24. The cavities can have a variety of thicknesses. For instance, the cavities can have a thickness in the range of about 0.1 millimeter to about 1.5 millimeters, and more preferably in the range of about 0.2 millimeters to about 0.75 millimeters. Other techniques can also be used to anchor the beams 22 and/or the proof mass platforms 24, such as incorporating retaining or anchoring elements onto the substrate 20.

The proof mass platforms 24 can be made of any number of materials and can have any configuration, shape, and size capable of supporting an external proof mass. In one embodiment the proof mass platforms 24 are made from the same material as the substrate 20 itself. In other embodiments it is made from a different material than the substrate, including a metal or a polymer. In the illustrated embodiment the proof mass platforms 24 are approximately rectangular and are approximately the same width as a width w of the beams 22. In other embodiments the proof mass platforms 24 can be generally square, generally elliptical, generally circular, generally triangular, generally trapezoidal, or any other number of shapes. As shown, a length of the proof mass platforms 24 extends between two troughs 26. However, in other embodiments the proof mass platforms 24 can be different sizes than any other component of the device 10, and even different sizes than other proof mass platforms of the device.

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As illustrated, the proof mass platforms 24 not only support the external proof mass 30, but they also provide an internal proof mass. This is more clearly illustrated in the fabrication process discussed with respect to FIGS. 5A-5I. In other embodiments, a
5 separate internal proof mass can be used in lieu of, or in addition to, the proof mass platforms 24.

The configurations of the devices 12 and the devices 10 in the illustrated embodiments provide for a symmetrical layout, which can help create uniform vibration throughout the beams 22. Such a symmetrical layout induces non-linear stretching of
10 the beam while minimizing the rotation and translation of the proof mass. Further, although in the illustrated embodiment there are four proof mass platforms 24, any number of proof mass platforms 24 can be used. Other techniques for coupling the external proof mass 30 to the piezoelectric beams 22 that do not require proof mass platforms 24 can also be used. The proof mass platforms 24 can include one or more
15 coupling features for coupling to the common external proof mass 30. As shown in the embodiment illustrated in FIGS. 6-9, the coupling feature includes receiving components for receiving protrusions on the external proof mass. Alternatively, the proof mass platforms 24 can be joined to an external proof mass using adhesive or bonding agents. In the device 10 of FIGS. 1-4, a bonding agent is used to allow a
20 mating component 32 of the external proof mass 30 to couple with the corresponding proof mass platforms 24.

Similar to the other components, the external proof mass 30 can be a variety of shapes, sizes, dimensions, and made from a variety of materials. In the illustrated embodiment, a size and shape of the external proof mass 30 is approximately the size
25 and shape of the substrate 20. However, this is not a requirement. The external proof mass 30 can be smaller or larger than the substrate 20 and can have a different shape than the substrate 20. For instance, the external proof mass 30 can be have a shape that can be described as generally rectangular, generally circular, generally elliptical, generally triangular, generally trapezoidal, or any other number of shapes. Further,
30 although in the illustrated embodiment the external proof mass 30 is a single proof mass, in other embodiments a plurality of external proof masses can be used. The plurality of external proof masses can be coupled in some fashion to assist in substantially synchronizing the force they apply to the beams 22. The proof masses can also be

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stacked on top of each other. Still further, the external proof mass can be made from a variety of different materials, but in one embodiment it is made of silicon.

5 The external proof mass 30 can generally include mating components 32 that are complimentary to components located on at least one of the proof mass platforms 24, the substrate 20, and the beams 22 so that the external proof mass 30 can be removably and replaceably coupled thereto. As shown, a bonding agent can be used to couple the mating components 32 to the respective proof mass platforms 24. As a result, the external proof mass 30 becomes coupled to the beams 22, thereby allowing the external
10 proof mass 30 to act on the beams 22 and create the desired stretching mode. Many other techniques can be used to couple the external proof mass 30 to the beams 22, including using magnetic materials, adhesives, or bonding agents, or by wafer bonding the external proof mass 30 to proof mass platforms 24.

15 While the external proof mass 30 can be made from a variety of different materials, it can generally be described as being heavier than the other components of the device 10. In one embodiment, a weight of the external proof mass is in the range of about 10 milligrams to about 5000 milligrams, and more preferably is at least about 50 milligrams. In one embodiment a weight of the external proof mass is about 180 milligrams. Like the other components of the device 10, the dimensions, weight, etc. of
20 the external proof mass will depend at least in part on the desired effects of the system, the size and capabilities of the components with which it will be used, and the desired resonance bandwidth and power output.

FIGS. 5A-5I illustrate the formation of an energy harvesting device that includes an internal proof mass 124, such as the proof mass platform 24 of the device 10. The
25 internal proof mass 124 is a thin and long structure, and in some embodiments, the beam itself can be capable of supporting a heavy proof mass. In other embodiments, such as the embodiment described above with respect to FIGS. 1-4, the beam works in conjunction with other beams and other components of an energy harvesting device to support a heavy proof mass.

30 As shown in FIG. 5A, the internal proof mass 124 is encompassed by a structural layer 152. The structural layer 152 can be a low-stress and high quality structural material, which can allow the internal proof mass 124 to withstand large strain during fabrication and performance. The structural layer 152 can be made of a variety of

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materials, but in the illustrated embodiment it includes a low pressure chemical vapor deposition nitride 153. Further, as shown, a low temperature oxide layer 151, such as a plasma enhanced chemical vapor deposition oxide, can be included to prevent a chemical reaction between materials such as silicon and lead that diffuses from one or more active layers 154 (as shown in FIG. 5B). Thermal oxidation can be performed on one or more of these layers. In another embodiment, the structural layer 152 can include silicon.

As shown in FIG. 5B, an active layer 154 can be introduced on a top portion of the structural layer 152. The active layer 154 can include a thin-film PZT that is deposited and patterned onto the structural layer 152. In one exemplary embodiment, the PZT is deposited by a sol-gel spin-coating method and is then patterned by way of wet or dry etching processes. Well-controlled rapid thermal annealing can transform the pyrolyzed ceramics into its Perovskite phase to ensure a strong piezoelectric performance. Other methods that can be used to deposit the thin-film PZT include sputtering, pulse laser deposition, and screen printing.

In some instances, the active layer 154 can also include a diffusion barrier. The diffusion barrier can block the diffusion of lead from PZT to the structural layer and its reaction with silicon. In the illustrated embodiment, the diffusion barrier is Zirconia (ZrO_2).

As shown in FIG. 5C, interdigitated electrodes 140 can be incorporated on top of the active layer 154. Instead of top and bottom electrodes, top interdigitated electrodes 140 are employed to collect the electrical charge generated in the PZT of the active layer 154 as a result of strain. In one exemplary embodiment, 2000Å of Platinum on top of 200Å of Titanium as adhesion layer are e-beamed. The electrodes can be patterned by lift-off method using AZ5214 photoresist and soaking in acetone overnight. A few minutes of ultrasound shaking can then ensure a complete lift-off, which can help avoid electrode shortages. A number of other methods to form interdigitated electrodes 140 can also be used.

As shown in FIG. 5D, a passivation layer 156 can be included. The passivation layer 156 can be placed over the active layer 154 and the interdigitated electrodes 140 to help prevent electrode shortages. The passivation layer 156 can electrically and chemically passivate the electrodes 140 and the active layer 154 throughout fabrication

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and performance. The passivation layer 156 also allows the resulting device to be easily cleaned, for instance after dry etching in Piranha solution. Without a passivation layer, the electrodes 140 could not be cleaned with a Piranha solution because the electrodes
5 140 would undesirably react with the solution. Further, by encapsulating the active layer 154, the robustness of the device will be enhanced, particularly if the device is exposed to harsh environments. In the illustrated embodiment, the passivation layer 156 includes a plasma enhanced chemical vapor deposition silicon nitride and a plasma enhanced chemical vapor deposition silicon oxide. As illustrated, the passivation layer 156 and
10 the structural layer 152 form a silicon nitride sandwich around the active layer 154.

As shown in FIG. 5E, the passivation layer 156 can be patterned to provide access to wire-bond pads 141 of the electrodes 140 for wire-bonding and packaging to the remainder of the device. Patterning can be accomplished in a number of ways, but in one embodiment etching is performed. Although many etching techniques can be used,
15 in one embodiment reactive ion etching is performed. Further, as shown in FIG. 5F, a top side portion of the structural layer 152, and thus the portions of the active layer 154 and the electrodes above the illustrated top portion of the structural layer 152, can be patterned, for example at location 157. Similarly, as shown in FIG. 5G, a back side portion of the structural layer 154 can be patterned, for example at location 159. Again,
20 while patterning can be accomplished in a number of ways, including by performing etching, in the illustrated embodiment reactive ion etching is performed. In alternative embodiments, heated potassium hydroxide etching can be performed in place of, or in conjunction with, reactive ion etching or other patterning techniques.

Still further, as shown in FIG. 5H, the internal proof mass 124 can be patterned,
25 for example at location 161. The illustrated embodiment indicates that the patterning occurs from the back side, but in other embodiments the patterning can occur from the top side. As shown, Xenon Difluoride (XeF_2) and deep reactive ion etching are used to pattern the internal proof mass 124. However, a number of other patterning and etching techniques can also be used.

30 FIG. 5I illustrates the resulting internal proof mass 124, which has piezoelectric properties. Further, FIG. 5I illustrates the resulting internal proof mass 124 being coupled to a substrate 120 and an external proof mass 130 being coupled to the resulting internal proof mass 124. As illustrated, both the substrate 120 and the external proof

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mass 130 are made of silicon. The substrate 120 can have properties similar to the properties discussed with respect to the substrate 20 of the device 10 of FIGS. 1-4. Likewise, the internal proof mass 124 can have properties similar to each of the beams 22, the proof mass platforms 24, and the electrode pairs 40 of the device 10 of FIGS. 1-4 because the internal proof mass 124 includes portions similar to each of these three components of the device 10. Still further, the external proof mass 130 can have properties similar to the properties discussed with respect to the external proof mass 30 of the device 10 of FIGS. 1-4.

FIGS. 6-9 illustrate another exemplary embodiment of an energy harvesting device 210. The device 210 is similar to the device 10 of FIGS. 1-4. For instance, it includes a substrate 220, a plurality of beams 222, a plurality of proof mass platforms 224, troughs 226, an external proof mass 230, and electrode pairs 240. These components have properties similar to the properties of the respective components as discussed above with respect to the device 10 of FIGS. 1-4. Further, as shown in FIG. 7, the plurality of proof mass platforms 224 include receiving components 225 for receiving the external proof mass 230. Likewise, the external proof mass 230 includes a plurality of protrusions 232 that are complimentary to the receiving components 225, thereby enabling the external proof mass 230 to be mechanically removably and replaceably coupled to the substrate 220.

The general form of dynamic force equilibrium of the energy harvesting devices 10 and 210 of FIGS. 1-4 and 6-9, respectively, in the σ and θ directions is:

$$\begin{cases} (k_B + k_{\sigma_0})\delta + k_s\delta^3 + C(\dot{\delta}, I_{Load}) + m_{pm}\ddot{\delta} = -m_{pm}A_{ex}\sin\omega_{ex}t \\ k_{\theta}\theta + k_{\sigma\theta}\sigma + m_{pm}\ddot{\theta} = 0 \end{cases} \quad (\text{Eqs. 3 and 4}).$$

This equation determines the possible deflections of the system. In these equations:

$$k_B = \left(\frac{\pi^4}{6}\right)\left(\frac{Ywt^3}{L^3}\right) \quad (\text{Eq. 5}),$$

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$$k_{\sigma_0} = \left(\frac{\pi^2}{2} \right) \left(\frac{\sigma_0 w t}{L} \right) \quad (\text{Eq. 6}), \text{ and}$$

$$k_s = \left(\frac{\pi^4}{8} \right) \left(\frac{Y w t}{L^3} \right) \quad (\text{Eq. 7}),$$

5 while δ is the beam deflection, $C(\dot{\delta}, I_{Load})$ is the total damping force, m_{pm} is the weight of the proof mass, A_{ex} is the excitation acceleration, ω_{ex} is the excitation frequency, and t is beam thickness. As discussed above, the devices 10 and 210 of FIGS. 1-4 and 6-9 are designed such that:

$$10 \quad k_B + k_{\sigma} \ll k_s Z^2 \quad (\text{Eq. 2}),$$

and thus the stiffness due to the bending and residual stress are negligible in view of the dominant nonlinear stiffness from the stretching.

Further, the deflection near the resonance can be approximated as:

15

$$\delta \approx \frac{Q A_{ex}}{(2\pi f)^2} \quad (\text{Eq. 8}),$$

where Q is the quality factor, and can be in micron range in view of typical values for the gain ($10 < Q < 100$), acceleration level ($0.1g < A_{ex} < 1g$), and frequency range (100
20 Hz–1kHz). Accordingly, the natural resonant frequency of the system can nearly match the excitation frequency:

$$\omega_n = \sqrt{\frac{k_B + k_{\sigma_0} + \frac{3k_s \delta^2}{4}}{m_{pm}}} \quad (\text{Eq. 9}).$$

25 The first inequality can require the thickness of the beam to be at most a few microns that can only be achieved at MEMS-scale. The second equality seems to be a more difficult condition to satisfy. It can mean that the stiffness from the residual strain in the

- 22 -

structure is much bigger than the bending stiffness for thin and large beams (diaphragm). To satisfy this condition, a high-quality, thin structural material can be used and the residual stress from the process can be controlled and kept as small as possible.

5 Furthermore, the length of the beams can be small enough to achieve the desired results, for example, not larger than a few millimeters.

FIG. 10 illustrates the theoretical roots of the governing nonlinear equation of motion given by Equation 3 for an embodiment in which the energy harvesting devices 10 and 210 of FIGS. 1-4 and 6-9 have an external proof mass that is approximately 180 milligrams mounted on an electro-mechanical shaker driven by an approximately 1.0 V input signal. The device 10 or 210 is excited by a sweeping sinusoid that ramps up from 500 Hz up to 2000 Hz. The output voltage of the energy harvesting device is monitored by a fast Fourier transform analyzer. For each excitation frequency, two components can be seen in frequency domain, which are illustrated in FIGS. 11 and 12. As
10 illustrated in FIG. 11, the first harmonic at the excitation frequency corresponds to the bending strain. As illustrated in FIG. 12, another harmonic at twice the frequency of excitation is generated due to the always-tensile stretching strain. The frequency of excitation in FIG. 12 is twice the frequency of the frequency in FIGS. 10 and 11 because the stretching occurs twice during a cycle of excitation.

20 As shown in FIG. 10, deflection first ramps up fairly steadily until approximately a frequency of about 1350 Hz. At that point, a sharp drop in both frequency and deflection occurs and the system no longer responds as desired. This sharp drop in deflection and energy is also reflected in FIGS. 11 and 12, where at approximately the same frequency (about 1350 Hz in FIG. 11 and about 2700 HZ in FIG. 12 because the harmonic is at twice the frequency of excitation) a sudden drop in voltage occurs. More specifically, FIG. 11 illustrates a steady increase of voltage until approximately a frequency of about 1350 Hz, while FIG. 12 illustrates a component that scale up quadratically as a function of frequency until approximately a frequency of about 2700 Hz. The component illustrated in FIG. 12, which is the voltage generated due to the stretching strain, is clearly the main source of power generation in view of the fact that
25 stretching occurs twice a cycle and further in view of the system's resonance to the incoming vibration. By increasing this component, high normalized power densities can be achieved—something linear energy harvesting devices cannot achieve. This is
30

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because only the devices of the present invention can extract energy more than the mechanical damping. More electric power can be extracted when the operational frequency is much lower than the jump-down frequency because it can tolerate higher electrical damping. This can allow devices of the present invention, such as the devices 10 and 210, to be scaled up to achieve electric power thresholds that more closely approach their theoretical power maximums.

For example, in some embodiments the MEMS-scale devices 10 and 210 of FIGS. 1-4 and 6-9 can approach electric power in the range of about 1 μ W to about 10 μ W at an excitation frequency of about 500 Hz, in the range of about 2 μ W to about 40 μ W at an excitation frequency of about 750 Hz, in the range of about 5 μ W to about 80 μ W at an excitation frequency of about 1000 Hz, and in the range of about 20 μ W to about 50 μ W at an excitation frequency of about 1300 Hz. By further optimizing the system, for instance by using a smart adaptive interface to draw more electrical energy from beams 22, 222 of the devices 10, 210, a sustainable power source of about 85 μ W or even greater than 100 μ W is possible. Likewise, as illustrated by FIG. 13, the devices 10 and 210 of FIGS. 1-4 and 6-9 can achieve normalized power densities that are greater than or equal to about 2 W per cm^3 , as shown by result 292, a normalized power density that had not been previously achievable according to a study performed by Khalil Najafi of the University of Michigan. Even without an external proof mass, a normalized power density beyond an excitation frequency of 1000 Hz can yield a normalized power density achieved by prior art devices only at frequencies below 1000 Hz, as shown by result 294.

An analysis of FIGS. 10-12 shows that it is preferable to keep the excitation frequency between two stabilization points, a minimum stabilization point 304 and a maximum stabilization point 306, to avoid any possibility of exceeding the breakdown excitation frequency while still maintaining a high enough frequency to obtain desirable deflection, and thus desirable voltage outputs. Although the stabilization points 304 and 306 are illustrated in FIG. 10, in the illustrated embodiment the stabilization points can be about 500 Hz and about 1300 Hz, and more preferably between about 700 Hz and about 1100 Hz. However, there are not currently components that are capable of maintaining the excitation frequency in a particular stabilization range defined by

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minimum and maximum stabilization points with MEMS-scale energy harvesting devices. The start-up circuit illustrated in FIG. 14 can help achieve this desired range.

5 The system 500 of FIG. 14 includes a dynamic model of nonlinear resonator 520, *e.g.*, the energy harvesting devices 10 and 210 of FIGS. 1-4 and 6-9, an envelope detector 560, and a control unit 570. The envelope detector 560 can detect the amplitude of vibration of the resonator 520. In the illustrated embodiment the envelope detector 560 includes a rectifier 562 and a low-pass filter 564. In case of small amplitude, the control unit 570 can be activated to exploit the actuation mode of a piezoelectric layer of
10 the resonator 520 during a start-up period. The sign of this constant voltage can be determined by the direction of velocity. As a result, the piezoelectric layer can apply a bending moment that is substantially synchronized with the motion of a proof mass of the resonator 520. The control unit 570 is increasing the amplitude of vibration by inducing a negative damping. Thus, both amplitude and frequency of vibration are
15 smoothly increased until they reach the high-energy stable regions, *i.e.*, the regions between the two desired stabilization points. Subsequently, the control unit 570 can detect this mode from the amplitude of vibration and disable the actuation, thus preventing the frequency from exceeding the desired stabilization point. In particular, the control unit 570 can both detect when the system is approaching a maximum
20 stabilization point and disable actuation to prevent the frequency from exceeding the maximum stabilization point and detect when the system is approaching a minimum stabilization point and enable actuation, thus preventing the frequency from falling below the minimum stabilization point. The system 500 has the ability to both start-up energy harvesting to occur more quickly, and further, the ability to maintain the
25 excitation frequency in a desired range to prevent an energy jump-off.

Further, if the excitation frequency does exceed a maximum stabilization point, thus causing the deflection and resulting voltage output to jump-off dramatically, the control unit 570 can also be configured to return the system 500 back to lower excitation frequencies that yield sufficient and desirable deflections and voltages. For example, if
30 the maximum stabilization point is approximately 1350 Hz as illustrated in FIG. 10, the control unit 570 can be configured to return the excitation frequency back to a frequency that allows the deflection, and thus the voltage outputs from the bending mode and particularly the stretching mode, to get back on track. With respect to FIG. 10, for

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example, the control unit 570 can return the excitation frequency to approximately 750 Hz, so the deflection can return to approximately 40 μm (as shown in FIG. 10), the bending-based voltage component can return to approximately 250 mV (as shown in FIG. 11), and the stretching-based voltage component to approximately 200 mV (as shown in FIG. 12). Alternatively, the control unit 570 can return the excitation frequency to approximately 600 Hz, so the deflection can return to approximately 20 μm (as shown in FIG. 10), the bending-based voltage component can return to approximately 200 mV (as shown in FIG. 11), and the stretching-based voltage component to approximately 100 mV (as shown in FIG. 12).

The circuit of the system 500 can be configured to consume a small amount of energy for a short period of time. Afterward, the system can go back to its energy harvesting mode and can compensate the energy consumed to start the system up in a short period of time. FIG. 15 illustrates a nonlinear energy harvesting device, like the devices 10 and 210 of FIGS. 1-4 and 6-9, without the start-up circuit illustrated in the system 500 being incorporated with the device. FIG. 16 illustrates a nonlinear energy harvesting device, like the devices 10 and 210 of FIGS. 1-4 and 6-9, with the start-up circuit illustrated in the system 500 being incorporated with the device. Without the actuation mode, the device stays in the low-energy region seemingly forever and oscillates at a very small amplitude. By activating the actuation mode, the amplitude of vibration can be increased slowly until the device reaches the high-energy mode. As illustrated in FIG. 16, the energy harvesting mode is activated after only about 70 time periods. Considering the typical frequency of vibration, which is about 100 Hz, 70 time periods corresponds to a start-up time of less than one second.

Although the system 500 is described for use with nonlinear energy harvesting devices like the devices 10 and 210 of FIGS. 1-4 and 6-9, the system 500 can be incorporated into any number of other devices in which a start-up circuit would lead to faster performance and/or any number of other devices in which maintaining or returning to a particular frequency range is desirable, including in other macro-scale or MEMS-scale energy harvesting devices.

Further, the systems, devices, and methods disclosed herein can be used in a variety of energy harvesting contexts because the systems, devices, and methods represent a low cost, small form factor that can be used in conjunction with devices like

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self-powering wireless sensors. For instance, harvesting power from environmentally available vibration is extremely useful for applications where no other power source than batteries, such as chemical batteries, are available, and thus the teachings contained
5 herein would be useful in this context. Two environmental type situations of this nature would include leak detection along a crude oil pipeline or air pollution measurement over a large, harsh terrain. The systems, devices, and methods disclosed herein can be used in a variety of other settings without departing from the spirit of the invention.

One skilled in the art will appreciate further features and advantages of the
10 invention based on the above-described embodiments. Accordingly, the invention is not to be limited by what has been particularly shown and described, except as indicated by the appended claims. All publications and references cited herein are expressly incorporated herein by reference in their entirety.

What is claimed is:

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CLAIMS:

1. A micro electro-mechanical system (MEMS) device for harvesting energy,
5 comprising:
at least one piezoelectric beam fixedly anchored at a first end to a substrate and
at a second end to a proof mass platform, the beam having a length dimension in a
direction between the first and second ends and configured such that external vibration
induces stretching of the beam in its length dimension;
10 a pair of electrodes electrically coupled to the beam and configured to extract
electrical energy from the beam; and
an external proof mass coupled to the proof mass platform.
2. The device of claim 1, wherein a stiffness of the beam is substantially nonlinear.
- 15 3. The device of claim 1, further comprising one or more piezoelectric layers
disposed on the beam.
4. The device of claim 1, wherein a length of the beam is about 100 millimeters or
20 less.
5. The device of claim 1, wherein the beam exhibits a ratio of thickness-to-
deflection in a range of about 0.01 to about 1.
- 25 6. The device of claim 1, wherein a deflection-to-length ratio of the beam is at least
greater than a square root of a residual stress-to-Young's modulus ratio.
7. The device of claim 1, wherein the device is configured to generate a power
density greater than or equal to about 1 Watt per cm^3 in response to external vibration.
- 30 8. The device of claim 1, wherein the external proof mass is at least about 50
milligrams.

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9. The device of claim 1, wherein the external proof mass is removably and replaceably coupled to the beam.
- 5 10. The device of claim 1, wherein the electrodes are interdigitated in a direction perpendicular to strain induced in the beam during vibration.
- 10 11. The device of claim 1, wherein a force vector applied by the proof mass is substantially perpendicular to the length of the beam and the device is configured such that a centerline extending from the beam in its length dimension intersects the proof mass force vector.
12. A micro electro-mechanical system (MEMS) device for harvesting energy, comprising:
- 15 a plurality of piezoelectric beams each fixedly anchored at a first end to a substrate and at a second end to a proof mass platform, the beams having a length, width, and thickness and configured such that external vibration induces stretching in the length dimension of the beam;
- 20 a pair of electrodes electrically coupled to each beam and configured to extract electrical energy from the beam; and
- an external proof mass coupled to the proof mass platform.
13. The device of claim 12, wherein a stiffness of the beams are substantially nonlinear.
- 25 14. The device of claim 12, further comprising one or more piezoelectric layers disposed on the beams.
15. The device of claim 12, wherein a length of the beams is about 100 millimeters or less.
- 30 16. The device of claim 12, wherein the beams exhibit a ratio of thickness-to-deflection in a range of about 0.01 to about 1.

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17. The device of claim 12, wherein a deflection-to-length ratio of the beams is at least greater than a square root of a residual stress-to-Young's modulus ratio.
- 5 18. The device of claim 12, wherein the device is configured to generate a power density greater than or equal to about 1 Watt per cm³ in response to external vibration.
19. The device of claim 12 wherein the external proof mass is at least about 50 milligrams.
- 10 20. The device of claim 12, wherein the external proof mass is removably and replaceably coupled to the beams.
21. The device of claim 12, wherein the pair of electrodes is interdigitated in a direction perpendicular to strain induced in the beams during vibration.
- 15 22. The device of claim 12, wherein a force vector applied by the proof mass is substantially perpendicular to the length of one of the beams and the device is configured such that a centerline extending from one of the beams in its length dimension intersects the proof mass force vector.
- 20 23. A micro electro-mechanical system (MEMS) device assembly for harvesting energy, comprising:
a plurality of the devices of claim 1 or claim 12 constructed on a common
25 substrate and wherein the devices share a common proof mass to induce substantially synchronized vibration and reduce phase differences in power generation.
24. The assembly of claim 23 wherein the devices are arranged in a non-parallel configuration.
- 30 25. The assembly of claim 23 wherein the beam length dimension of one device is substantially perpendicular to the beam length dimension of another device.

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26. The assembly of claim 23, further comprising a plurality of proof mass receiving platforms each having a coupling feature for coupling to the common proof mass.

5 27. The assembly of claim 23, wherein the plurality of devices are disposed in four quadrants that are equally disposed from a center of the assembly and the proof mass receiving platforms are disposed centrally within each quadrant.

28. A micro electro-mechanical system (MEMS) device for harvesting energy,
10 comprising:

at least one piezoelectric beam fixedly anchored at a first end to a substrate and at a second end to a proof mass, the beam configured such that external vibration induces stretching of the beam in its length dimension;

15 a pair of electrodes electrically coupled to the beam and configured to extract electrical energy from the beam, wherein the device is configured to generate a power density greater than or equal to about 1 Watt per cm³ in response to external vibration.

29. A method for harvesting energy, comprising:

20 detecting an amplitude of vibration of an energy harvesting device having a piezoelectric component and a proof mass; and

activating a control unit to exploit an actuation mode of the piezoelectric component of the energy harvesting device to activate a bending moment that is substantially synchronized with a motion of the proof mass.

25 30. The method for harvesting energy of claim 29, wherein the amplitude and frequency of vibration of the energy harvesting device achieve a high-energy stable region in less than one second.

31. The method for harvesting energy of claim 29, further comprising:

30 detecting an approach of a maximum stabilization point;

disabling actuation to prevent the frequency from exceeding the maximum stabilization point.

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32. The method for harvesting energy of claim 31, further comprising:
detecting an approach of a minimum stabilization point;
enabling actuation to prevent the frequency from falling below the minimum
5 stabilization point.
33. A resonating device for harvesting energy, comprising:
at least one piezoelectric beam fixedly anchored at each of a first end and a
second end;
10 a pair of electrodes electrically coupled to the beam and configured to extract
electrical energy from the beam, wherein the device is configured such that the electrical
energy extracted by the pair of electrodes is greater than the mechanical damping that
can be extracted.

1/10

FIG. 1

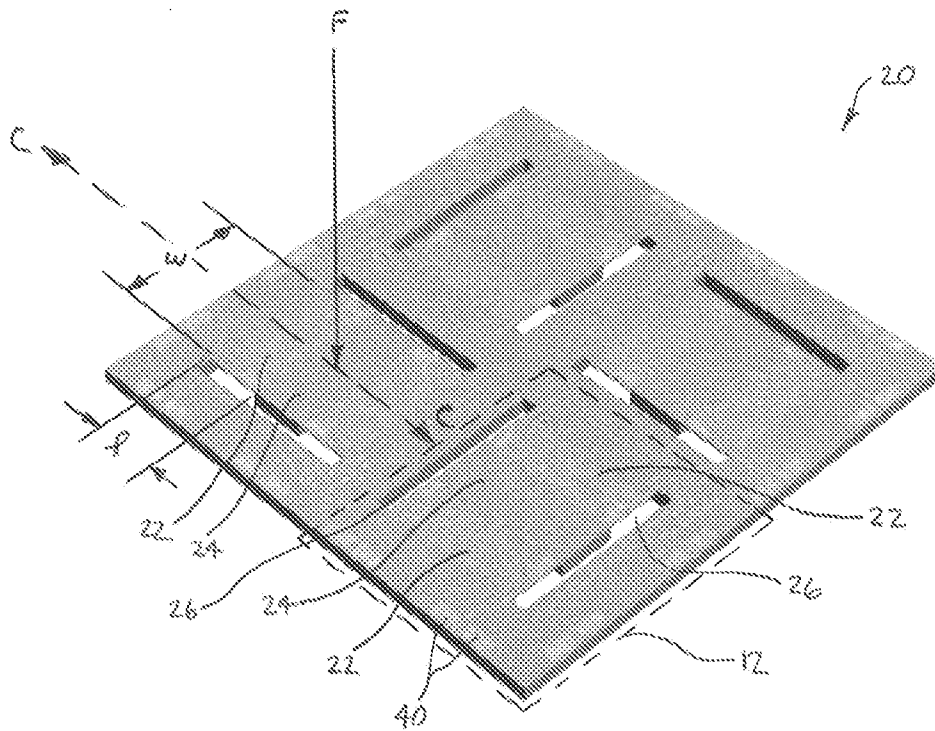
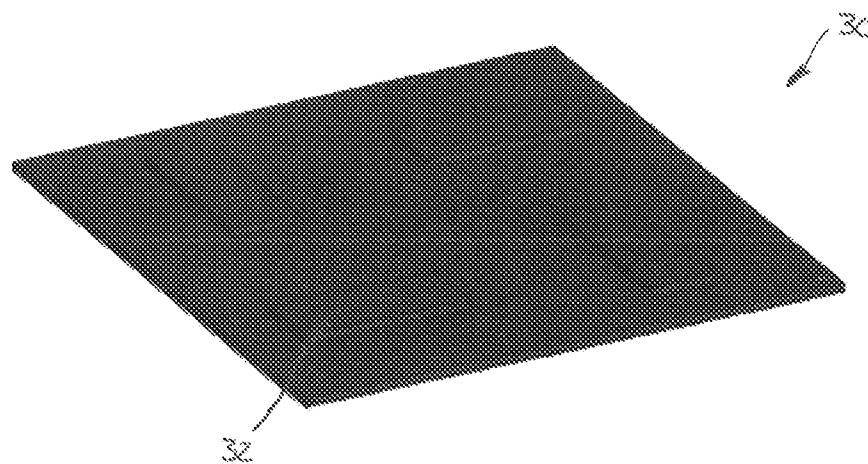


FIG. 2



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FIG. 3

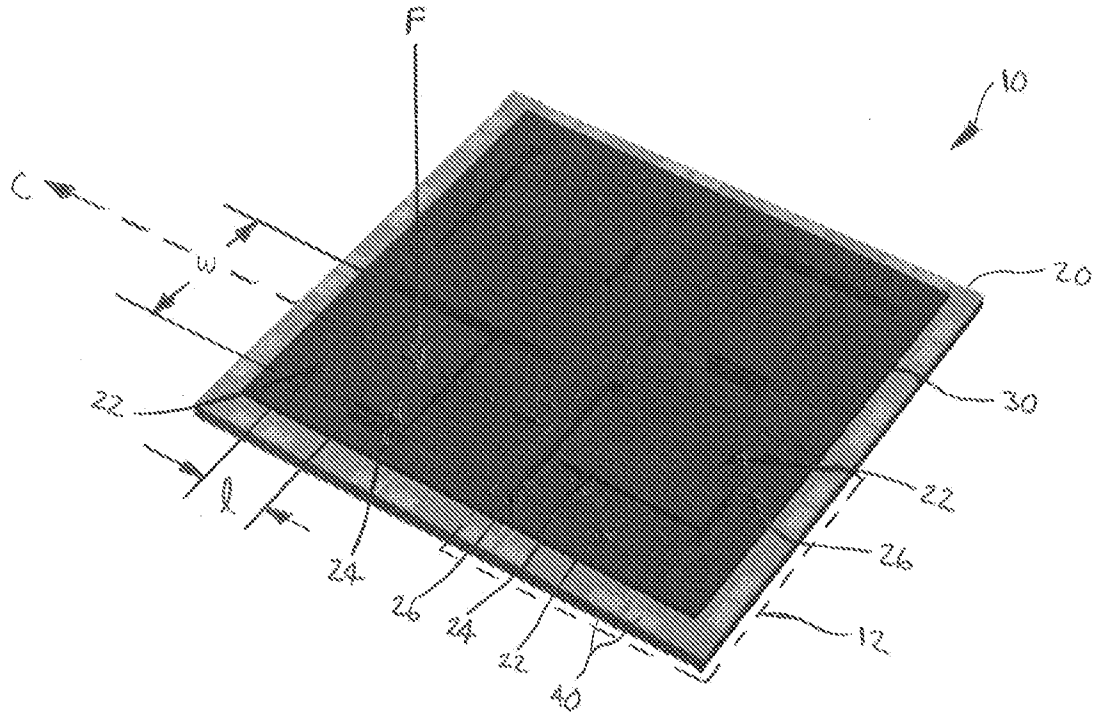
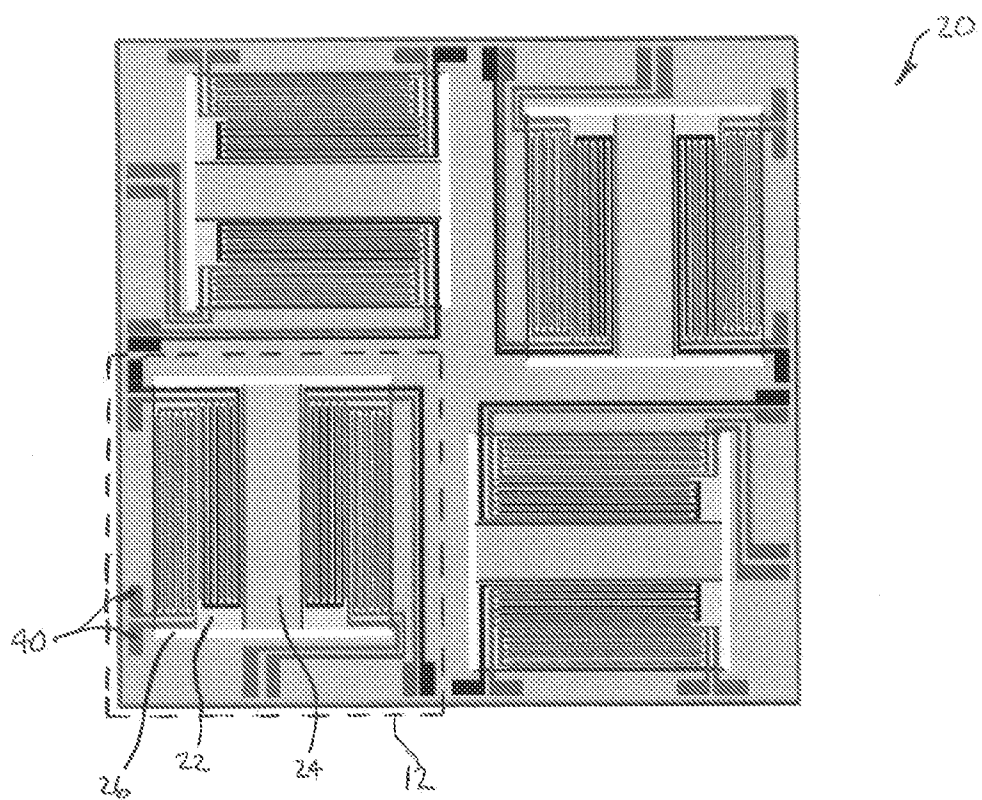
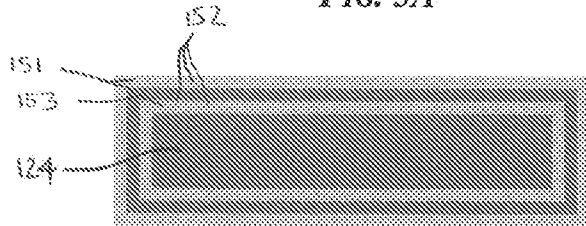


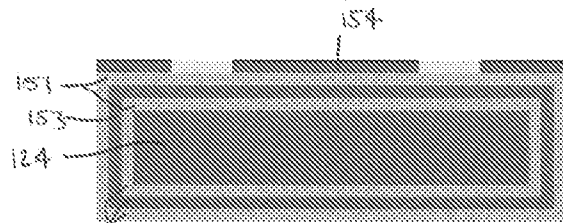
FIG. 4



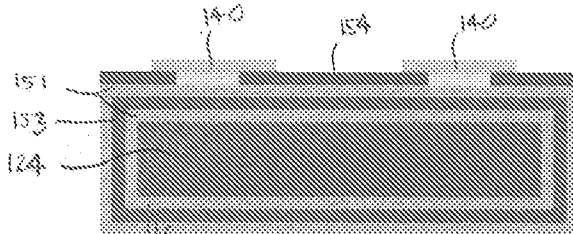
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FIG. 5A

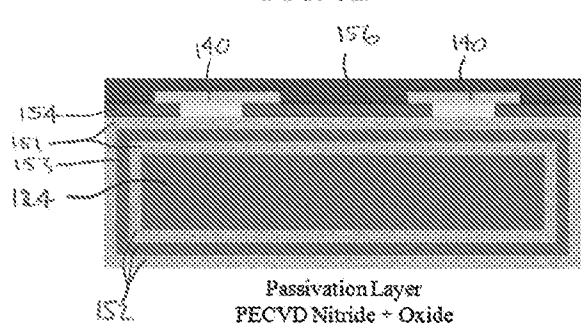
Structural Layer
Thermal Oxidation + LPCVD Nitride + LTO
Post Annealing

FIG. 5B

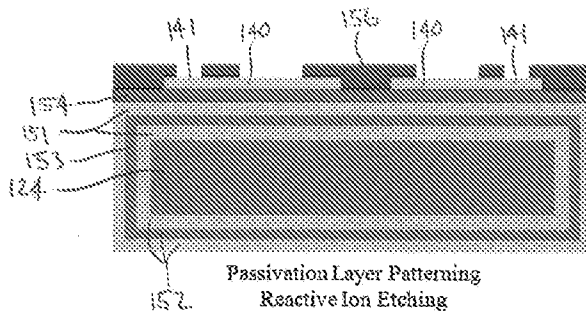
Active Layer
 ZrO_2 (Spin-coating/Pyrolysis/Wet Etch/Anneal)
+ PZT (Spin-coating/Pyrolysis/Wet Etch/Anneal)

FIG. 5C

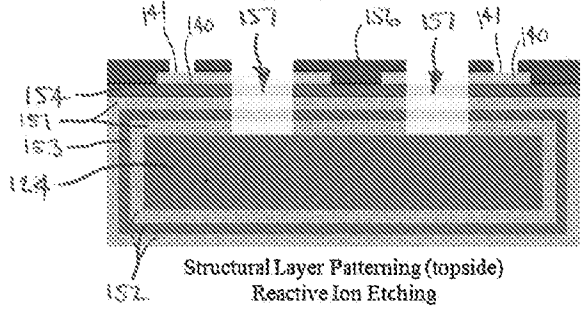
Interdigitated Electrodes
Ebeam Ti/Au or Ti/Al
Lift-off Method

FIG. 5D

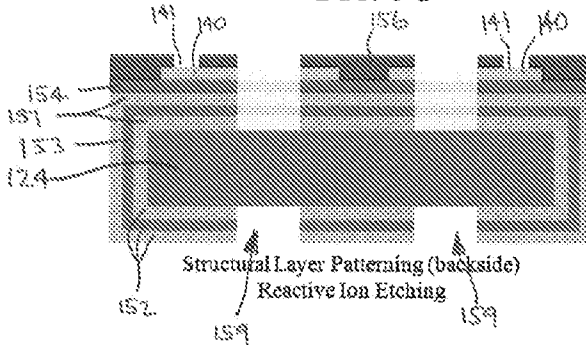
Passivation Layer
PECVD Nitride + Oxide

FIG. 5E

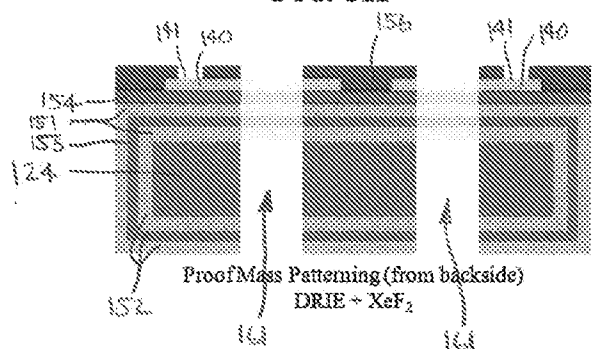
Passivation Layer Patterning
Reactive Ion Etching

FIG. 5F

Structural Layer Patterning (topside)
Reactive Ion Etching

FIG. 5G

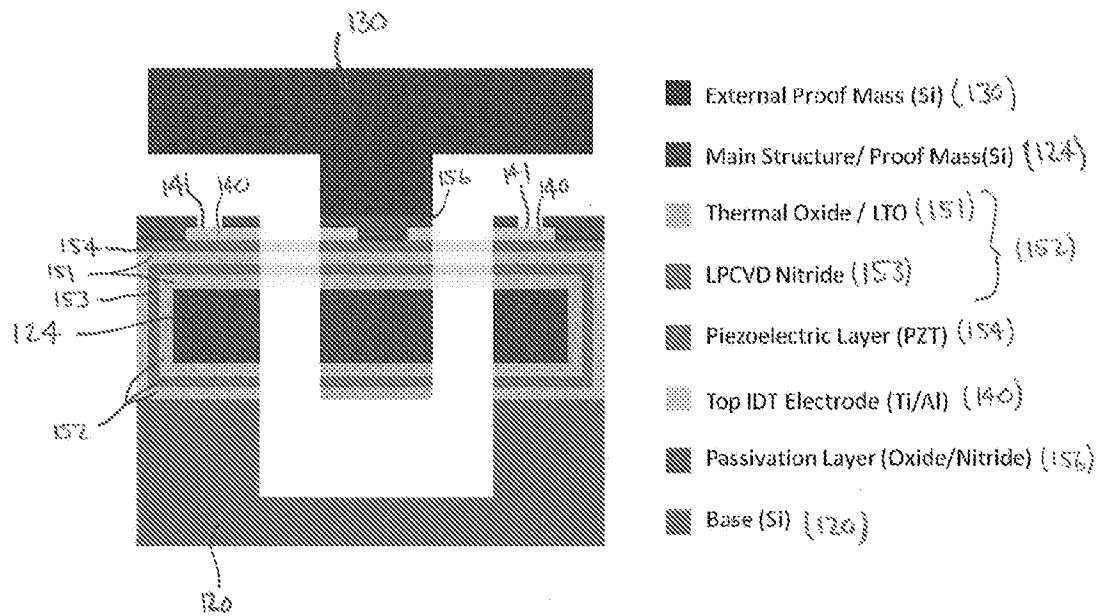
Structural Layer Patterning (backside)
Reactive Ion Etching

FIG. 5H

Proof Mass Patterning (from backside)
DRIE + XeF₂

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FIG. 5I



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FIG. 6

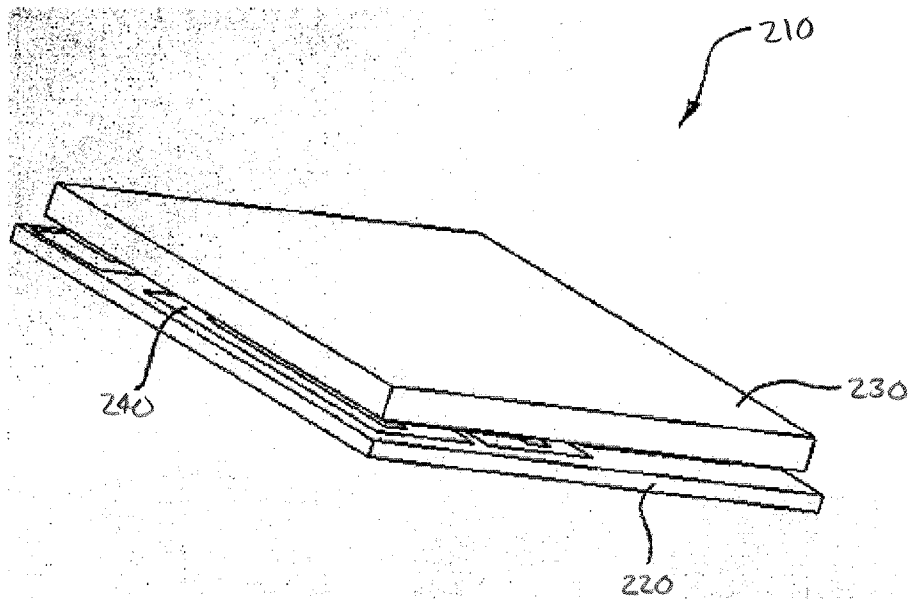
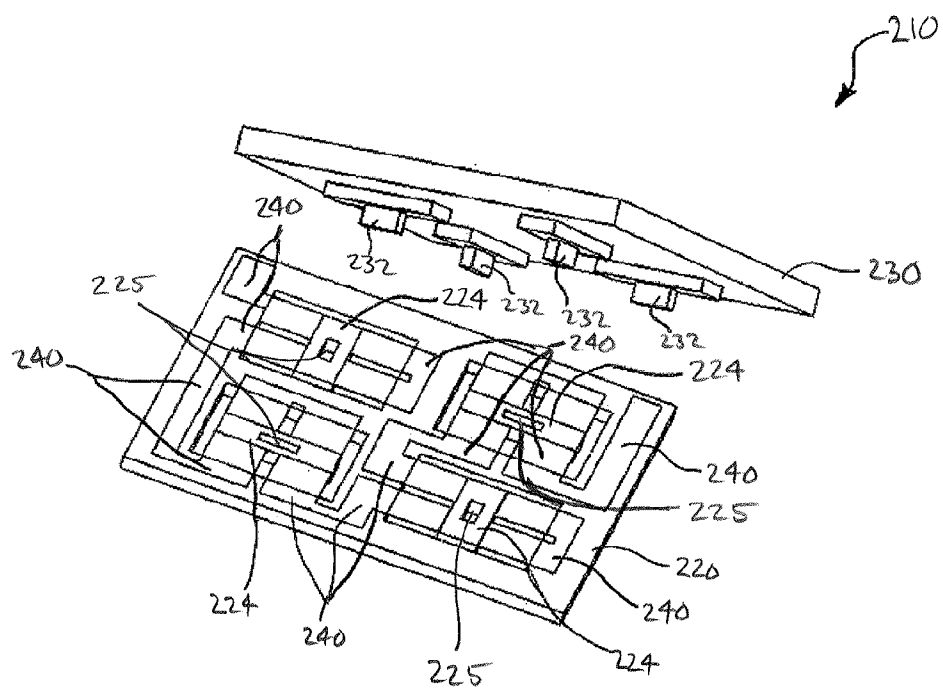


FIG. 7



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FIG. 8

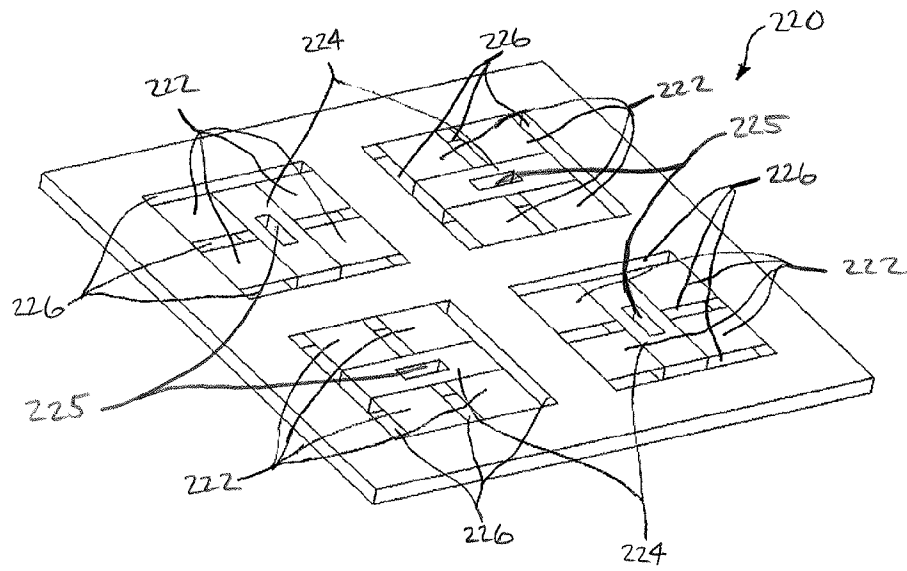
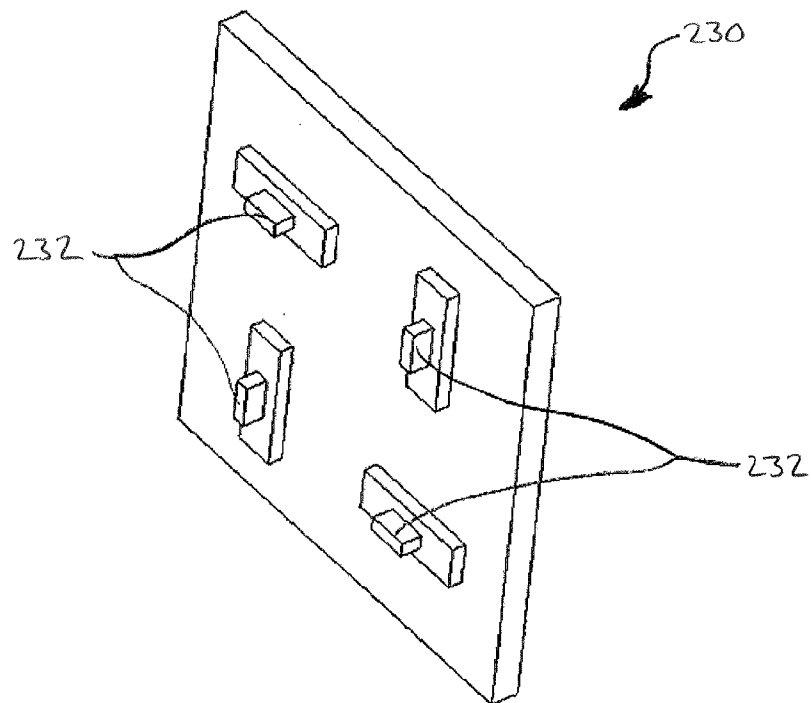


FIG. 9



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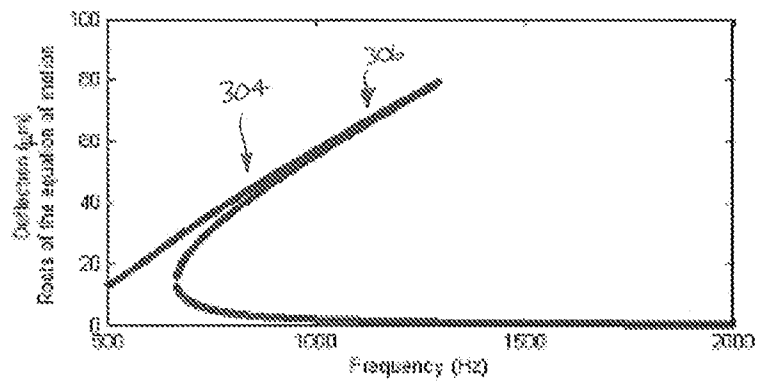
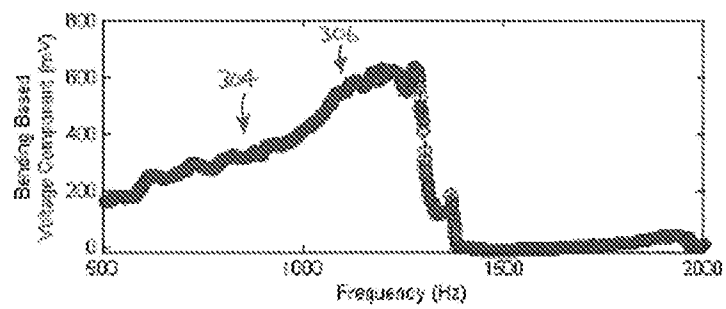
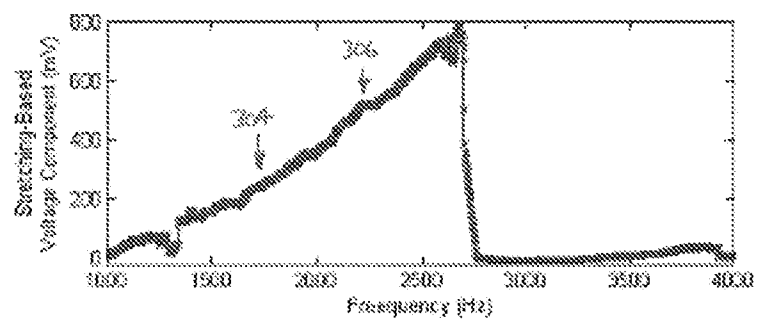
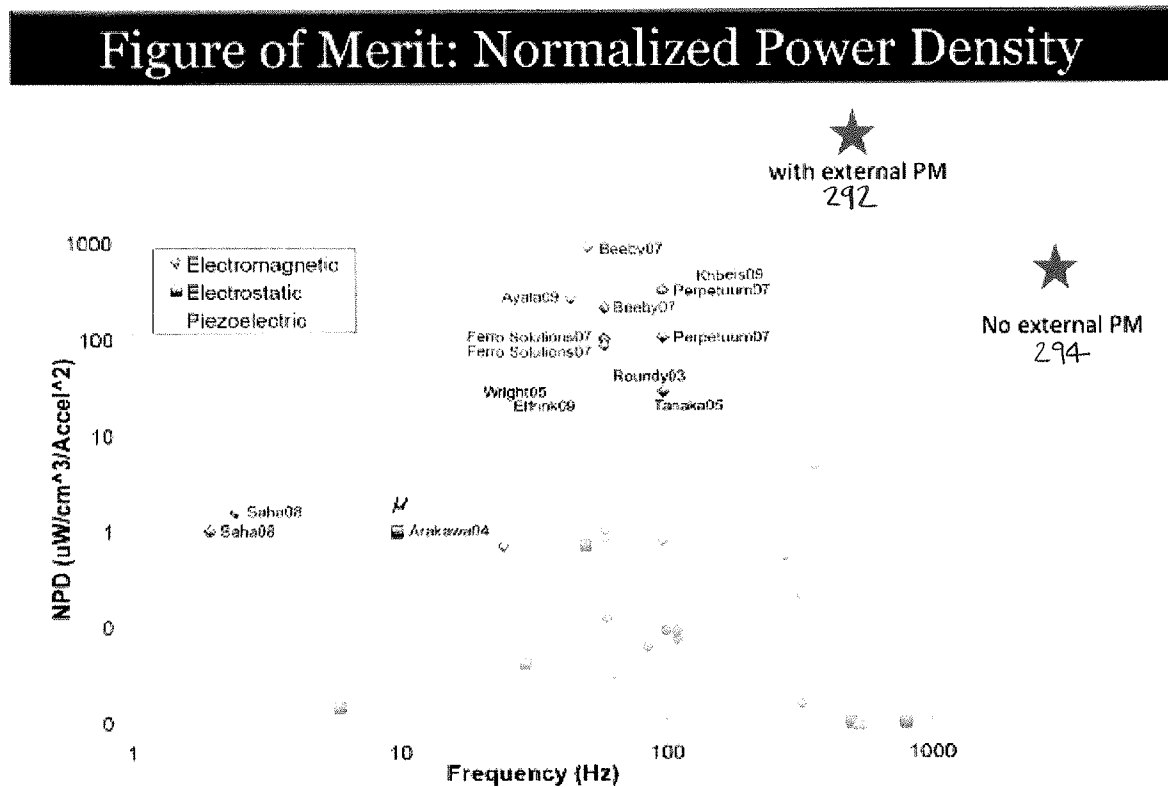
FIG. 10*FIG. 11**FIG. 12*

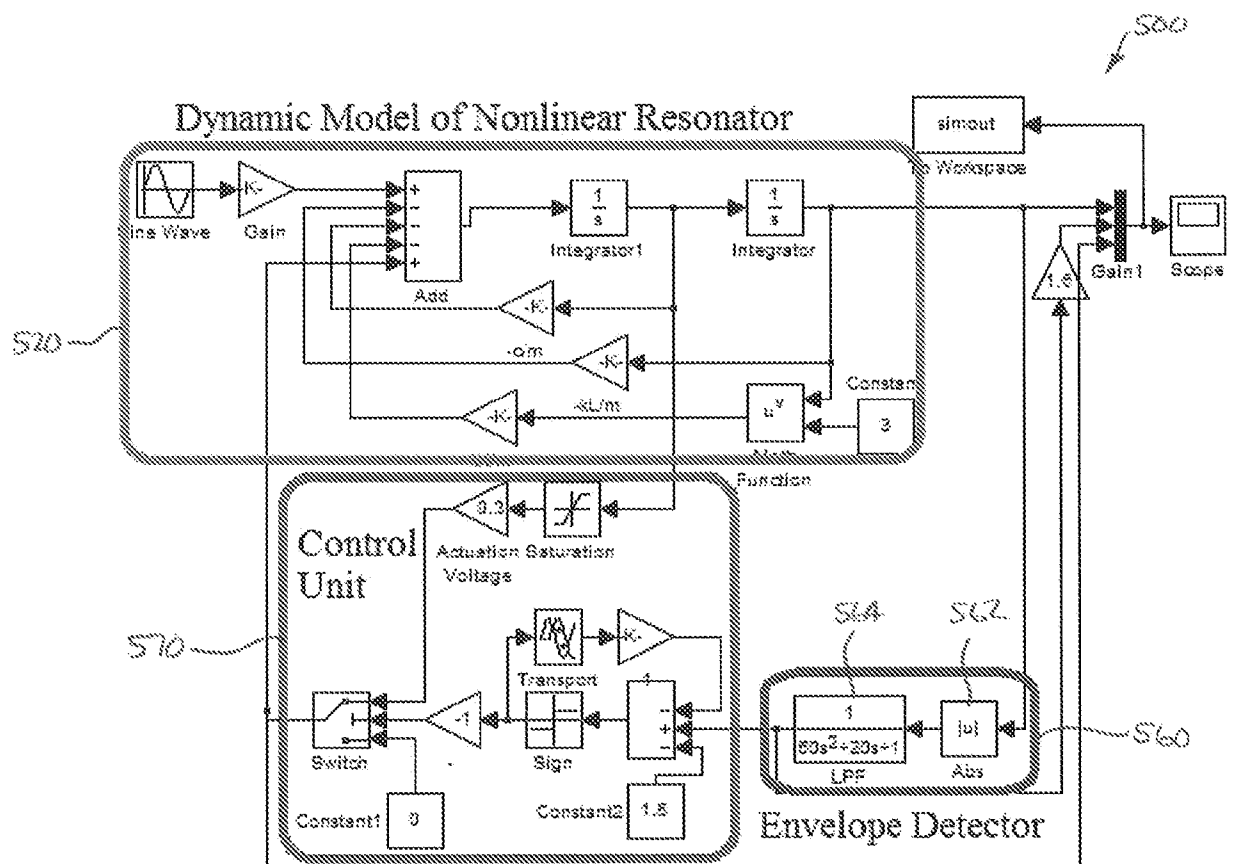
FIG. 13



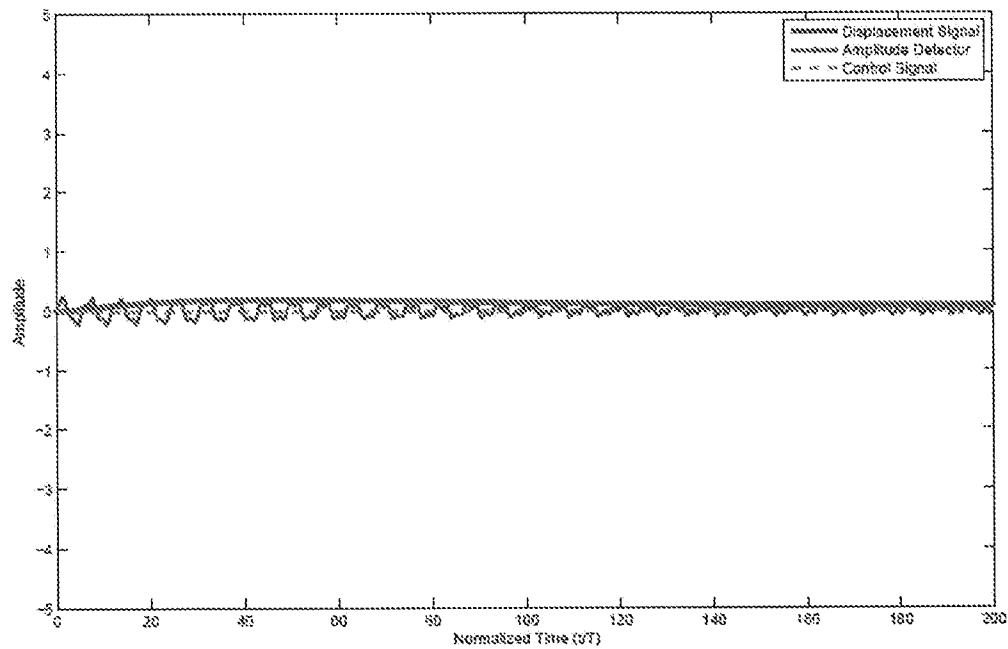
Comparison of various Energy Harvesting Devices by Khalil Najafi, University of Michigan

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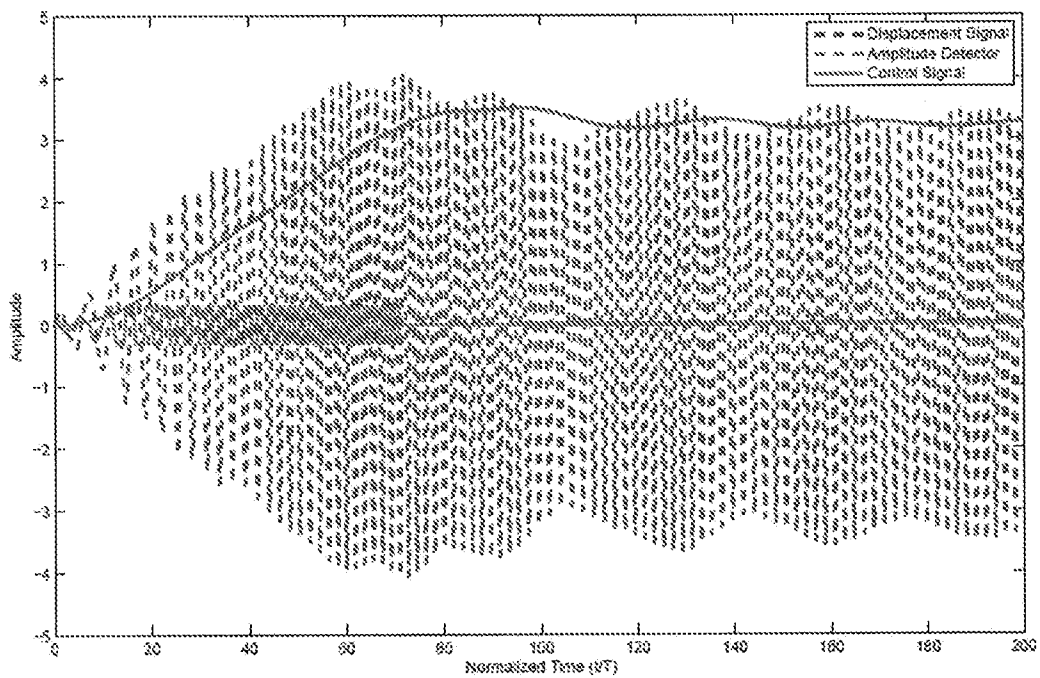
FIG. 14



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FIG. 15

inactive

FIG. 16

active