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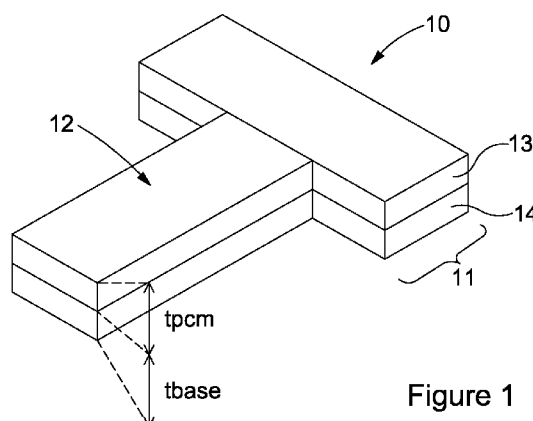


Figure 1

(57) Abstract: A mechanical resonator (10) having a resonant structure (12). The resonant structure (12) comprises a first mechanical layer (14) supporting a phase change material (13). The phase change material (13) has a first solid phase and a second, different, solid phase. A natural frequency of a vibration mode of the resonant structure (12) varies in response to changing the phase of the phase change material (13) from the first solid phase to the second solid phase.

TUNEABLE RESONATOR

The invention relates to a tuneable mechanical resonator and to an actuator.

5 MEMS (micro-electromechanical systems) and NEMS (nano-electromechanical systems) have found applications in a wide array of technologies such as sensors, low-leakage electronics, nanoscale imaging, health monitoring systems and digital micromirror arrays. In many new emerging applications, especially those of NEMS, mechanical resonators are operated at their natural resonant frequency. Small
10 perturbations to the free motion of such a resonator can be observed by monitoring the resonant frequency, or by monitoring spectral characteristics the frequency response of the resonator. In addition, because of the potential for extremely high quality factors (Q) in MEMS and NEMS resonators, a range of high-quality frequency filtering and mixing applications (important features in wireless, global positioning
15 and mobile systems) may be implemented using micro or nanoscale resonators.

Telecommunication systems may use on electronic oscillators to generate the fundamental frequencies needed during mixing and filtering. In a known receiver architecture, an antenna receives a baseband signal at a baseband frequency. The
20 output of the antenna may be filtered by a first bandpass filter and then mixed with the output of a local oscillator by a mixer. Heterodyne signals having an intermediate frequency are produced by the mixing, having frequencies of the baseband frequency plus or minus the local oscillator frequency. Other unwanted additional frequencies may also be created as a result of unwanted inter-modulation products. A further
25 bandpass filter may be used to filter out all frequencies except the desired intermediate frequency (e.g. the baseband frequency minus the local oscillator frequency). Further signal processing (e.g. demodulation) can then take place on the intermediate frequency signal, which may be at a reduced frequency.

30 A high quality signal from the local oscillator is important in achieving low noise and high performance in the receiver. When multiple frequencies (or bands) are needed, it may be necessary to include multiple local oscillators within the same system. Traditionally, piezoelectric materials, such as quartz, have been used to realise high quality oscillators. Integrating such materials with standard silicon technology (e.g.
35 CMOS processing) has proven difficult. Oscillators comprising MEMS resonators are

known (Lutz, M., et al. "MEMS oscillators for high volume commercial applications." *Solid-State Sensors, Actuators and Microsystems Conference, 2007. TRANSDUCERS 2007. International. IEEE, 2007*), and are commercially available (see www.discera.com and www.sitime.com).

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In addition to their applications as oscillators, mechanical resonators can be used directly as mechanical bandpass filters (see Nguyen, CT-C. "MEMS technology for timing and frequency control." *Ultrasonics, Ferroelectrics, and Frequency Control, IEEE Transactions on* 54.2 (2007): 251-270).

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The resonant frequency of a mechanical resonator is mainly defined by its physical properties (e.g. structure and materials). The structure and materials, and therefore frequency of operation are chosen at the fabrication stage. It is desirable to be able to tune (or change) a resonant frequency of a mechanical resonator after it has been produced, for instance to compensate for temperature induced changes in resonant frequency, or to allow the selection of a desired frequency (e.g. corresponding with a desired channel).

15

MEMS and NEMS resonator can be weakly tuned in frequency using a constant electrostatic force to act on the motion of the cantilever (for example, see Buks, E. and Roukes, M. L. "Electrically Tunable Collective Response in a Coupled Micromechanical Array" *Journal of Microelectromechanical systems*, (2002) 11, (6)). Such frequency tuning may be achieved by providing a stationary electrode adjacent to the resonator, and a conducting layer comprised as part of the resonating structure. A voltage bias between the resonating structure and adjacent electrode results in an electrostatic force that increases with decreasing gap between the resonating structure and stationary electrode. This can be thought of a negative electrostatic spring, that acts to reduce a resonant frequency of a mode of the resonator by reducing the effective spring constant associated with that mode.

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One drawback of electrostatic tuning is that it requires a constant bias voltage to be maintained. A resonator in which a change in resonant frequency is maintained without power is desirable. Furthermore, the amount of tuning that can be achieved electrostatically is dependent on the gap (between resonator structure and stationary electrode) and the maximum available bias voltage. The practical tuning range may

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therefore be relatively limited. In addition, large changes in frequency may result in the non-linearity of the electrostatic spring becoming a significant factor, resulting in an amplitude dependent resonant frequency, and the potential for instability at large amplitudes of vibration.

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A resonator that overcomes at least some of the above problems is desired.

According to a first aspect of the invention, there is provided a mechanical resonator having a resonant structure and phase changing means, wherein the resonant structure comprises a first mechanical layer supporting a phase change material (PCM), the
10 phase change material having a first solid phase and a second, different, solid phase, wherein the phase changing means is operable to vary a natural frequency of a vibration mode of the resonant structure by changing the phase of the phase change material from the first solid phase to the second solid phase.

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The first and second solid phase may be substantially stable (e.g. metastable) at standard temperature and pressure (based on the NIST definition of 20°C and an absolute pressure of 1 atmosphere).

20 The vibration mode of the resonant structure may have a Q of at least 10, 100, 1000, 10^4 , 10^5 , 10^6 , or 10^7 . For the structure to resonate, the vibration mode must be underdamped (by definition), but the Q is preferably high, so that a narrow spectral response is obtained at resonance. The resonator may be packaged at a low ambient pressure, to reduce losses due to damping (e.g. squeeze film damping).

25

Such a resonant structure is capable of changing resonant frequency on demand, to allow a desired natural frequency of operation to be selected. The desired frequency may be maintained without the need for constant power or a constant tuning voltage. In addition, an extended tuning range may be achieved by exploiting the large change
30 in mechanical properties that may accompany a phase change.

35

The resonant structure may be defined as the part of the mechanical resonator that participates in the vibration mode (e.g. the parts having a non-negligible modal displacement magnitude).

The phase change material may comprise germanium-antimony-tellurium, or GST. GST is a well understood phase change material in the context of optical and electrical properties, and has applications in phase-change memory. GST can readily be deposited, and has significantly different elastic properties in the amorphous and crystalline phases.

The PCM may comprise a chalcogenide glass. The PCM may comprise a material selected from: InSe, SbSe, SbTe, InSbTe, GeSbTe, GeSbTeSe, AgInSbSeTe, AgInSbTe, and GeTeSbS.

A second mechanical layer may be provided. The phase change material may comprise a phase change material layer between the first and second mechanical layers. Placing the phase change material between the first and second mechanical layers may protect the phase change material from the environment, for example, to prevent oxidation thereof.

The first mechanical layer may comprise (or consist entirely of) graphene. The second layer may comprise (or consist entirely of) graphene. Using graphene as a mechanical layer may be advantageous because such layers are very thin, so are appropriate for an application where a large tuning range is required because they allow the PCM to contribute a greater proportion of the effective stiffness. Furthermore, graphene layers are electrically conducting, so may be used as electrodes for providing a current pulse to change the phase of the PCM, or for electrostatic transduction (to perform at least one of driving, readout and tuning).

The first and second mechanical layers may comprise electrically conductive material, the first and second mechanical layers being configured to change the phase of the phase change material by passing a current through the phase change material via the first and/or second mechanical layers.

The mechanical resonator may comprise an electrically conducting track adjacent to the phase change material, wherein electrically conducting track is operable to change the phase of the phase change material by joule heating (i.e. resulting from the passing of current) of the conducting track. This may substantially reduce the voltage and/or current required to change the phase of the phase change material, in comparison with

arrangements which rely on direct joule heating of the phase change material by passing a current through the phase change material.

5 The mechanical resonator may further comprise a stationary electrode adjacent to the resonant structure. The resonant structure may comprise a moveable electrode, the stationary and moveable electrodes being configured for electrostatic tuning of a resonant frequency of the resonant structure. Electrostatic tuning may complement the range of tuning provided by changing the phase of the phase change material, for example being more limited in range, but having a substantially continuous range of
10 adjustment.

The first mechanical layer and/or second mechanical layer may have a thickness of less than 100nm, or less than a thickness selected from 200nm, 150nm, 50nm, 30nm, 10nm or 5nm. The first and/or second mechanical layer may be atomically thin. The
15 first and/or second mechanical layer may comprise (or consist entirely of) a material selected from: graphyne, borophene, silicone, stanane, phosphorene, graphene, germanane, tungsten diselenide, tungsten disulphide and molybdenum disulphide. A thin mechanical layer enhances the amount of frequency tuning as a result of a change in phase of the phase change material. This is because a thin mechanical layer means
20 the mechanical properties are less dominated by the substantially fixed mechanical properties of the mechanical layer, so the changes in the mechanical properties of the phase change material have a greater effect.

The resonant structure may comprise: a membrane, a cantilever, a bridge, a free-free
25 beam (having free ends, supported at vibrational nodes), a ring, a disk, and/or a tuning fork. Resonators based on such structures may all be tuned by varying the mechanical properties of part of the resonating structure by changing a phase of a material comprising at least part of the resonant structure.

30 The resonant structure may be a membrane, and the vibration mode may be a transverse membrane vibration mode.

A lateral dimension of the membrane may be less than: 1mm, 100microns, 10 microns, 1 micron or 100nm. A small lateral dimension may be advantageous in achieving a

relatively high frequency of operation (e.g. corresponding with telecommunications bands such as GSM) with a thin mechanical layer.

5 The mechanical resonator may further comprise an excitation means for driving the vibration mode of the resonant structure. The excitation means may comprise a laser for opto-mechanically driving the resonator (for instance by pulsed heating of one side of the resonator). Alternatively an electrostatic transducer comprising the stationary and moving electrode may be used to drive the vibration mode.

10 The mechanical resonator may further comprise sensing means for detecting the vibration mode of the resonant structure. The sensing means may comprise a light sensing element for optically detecting the vibration of the resonant structure. Alternatively, the sensing means may comprise an electrical circuit for detecting a displacement current arising from a change in mutual capacitance between a moving
15 electrode comprised as part of the resonator and a stationary electrode adjacent thereto (i.e. electrostatic transduction).

The mechanical resonator may comprise a piezoresistive element, arranged to change resistance as a consequence of a displacement corresponding with the vibration mode.

20 The mechanical layer may comprise the piezoresistive element. The mechanical layer may comprise a piezoresistive material, so that the whole mechanical layer comprises the piezoresistive element. Graphene is a piezoresistive material, so where the mechanical layer comprises graphene, piezoresistive transduction may be used to detect vibration of the resonant structure, based on a modulation of the resistance of
25 the mechanical layer due to the vibration.

According to a second aspect of the invention, there is provided an oscillator comprising a mechanical resonator according to the first aspect (or an array of such resonators).

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According to a third aspect, there is provided a bandpass filter comprising a mechanical resonator according to the first aspect (or an array of such resonators).

An array of resonators may be useful for achieving a higher signal to noise ratio in the
35 sensing means. Detecting the vibration of a single resonator may be challenging,

especially if their dimension is small. In the case of electrostatic transduction, an array of devices may reduce the motional resistance of the resonator, improving the ease with which the resonators may be driven and their vibration sensed.

- 5 According to a fourth aspect, there is provided a mobile communication device comprising the oscillator of the second aspect or the bandpass filter of the third aspect.

According to a fifth aspect, there is provided a method of making a mechanical
10 resonator, comprising the steps of:

forming a recess in a fixed layer of a substrate;
transferring a first graphene layer onto the substrate;
depositing a phase change material on the first graphene layer; and
transferring a second graphene layer onto the phase change material.

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This provides a convenient way of producing a resonator in accordance with the first aspect.

The recesses in the fixed layer may be formed before the first layer is transferred onto
20 the substrate. The method may further comprise a step of depositing the first or second graphene layer by chemical vapour deposition (CVD). CVD graphene may have a lower cost than other types of graphene, but may be suitable for use as a mechanical layer.

25 The step of depositing the phase change material may comprise sputtering the phase change material. The phase change material may comprise germanium-antimony-tellurium.

The invention is not restricted only to resonators, and other applications for phase
30 change materials in MEMS and NEMS devices are envisaged.

According to a sixth aspect, there is provided an actuator comprising a cantilever, the cantilever comprising a first mechanical layer supporting a phase change material, the phase change material having a first solid phase and a second, different, solid phase,

wherein the cantilever is displaced in response to changing the phase of the phase change material from the first solid phase to the second solid phase.

According to a seventh aspect a radio frequency switch is provided, comprising the
5 actuator of the sixth aspect.

The cantilever may be displaced from a first position to a second position in response to changing the phase of the phase change material, and the cantilever may comprise a
conducting element that provides an electrical path between two separated conductors
10 in a first position, and which provides electrical isolation between two separated
conductors in the second position.

The electrical path provided by the conducting element may be by contact between the
conducting element at least one of the separated conductors.
15

The electrical path provided by the conducting element may be by capacitive coupling
between the conducting element and at least one of the separated conductors.

At least one of the separated conductors may be part of a coplanar waveguide.
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Embodiments of the invention will now be described, purely by way of example, with
reference to the accompanying drawings in which:

Figure 1 is a schematic view of a cantilever resonator comprising a single mechanical
25 layer according to an embodiment;

Figure 2 is a graph that indicates how control of the phase of a phase change material
may be achieved by varying the temperature of the layer over time;

30 Figure 3 is a graph showing, for the embodiment of Figure 1 a relationship between
both a phase change voltage (V_{th}) and the amount of frequency tuning ($\Delta F_{\%}$) that
results from a phase change, with a ratio of the thickness of the first mechanical layer
and the thickness of the phase change material layer;

Figure 4 is a sectional diagram of a fixed-fixed beam resonator comprising a single mechanical layer according to an embodiment;

Figure 5 is a sectional view of a resonator comprising a first and second mechanical layer according to an alternative embodiment;

Figure 6 is a schematic diagram of a membrane resonator according to a further embodiment;

Figure 7 is a graph showing the relationship between design parameters of a resonator and the resonant frequency thereof;

Figure 8 is a graph showing the relationship between design parameters of a resonator and the tuneability thereof;

Figure 9 is a block diagram of a receiver architecture according to an embodiment; and

Figure 10 shows a first and second process flow by which a resonator according to an embodiment may be realised.

Referring to Figure 1, a mechanical resonator 10 is shown, comprising a mechanical layer 14 and a phase change material layer 13. A fixed region 11 of the layers is fixed to a substrate (not shown), and a resonating structure 12 in the form of a cantilever is defined comprising both the mechanical layer 14 and the phase change material layer 13.

The mechanical layer 14 may comprise any suitable material, such as silicon (crystalline or polycrystalline) or silicon nitride. The phase change material layer 13 may comprise any phase change material having mechanical properties that are altered during a phase change. The change in mechanical properties of the phase change material layer 13 changes the natural frequency of the cantilever 12.

Phase change materials (PCM), as defined herein are functional materials that possess two stable and reversible phases, with distinguishable mechanical properties. An

example of a suitable PCM is germanium-antimony-tellurium or GST (for example, $\text{Ge}_2\text{Sb}_2\text{Te}_5$).

Figure 2 is a graph of a suitable stimuli for inducing a phase change in a PCM. A first stimulus 23, increasing the temperature of a region of PCM above the characteristic transition temperature (T_c) results in crystallisation of an initially (e.g. as-deposited) amorphous PCM 22 in the region. Once in the crystalline phase 21, the region can be reverted back to the amorphous state 22 by using a second higher temperature stimulus 24 (above a melting temperature, T_m), having a shorter duration. The rapid removal of heat in the second stimulus 24 means that the material does not have time to re-organise into the crystalline phase, and is instead locked in the amorphous phase.

Many of these transformations occur in timescales of nanoseconds or less and are substantially stable at room temperature, which makes them well suited for electronic applications that require high speed. Much of the previous research on PCMs has focused on their ability to store information in the form of their physical state, both in the optical domain (for use as a re-writable optical storage medium) and electronic domain (as a potential future replacement for charge based non-volatile memory). More recently the optoelectronic properties of PCMs have been explored, with applications demonstrated in ultra-high resolution nano-displays. The application of PCMs to electromechanical and optomechanical devices has not hitherto been explored.

Recent experiments have shown that the Young's modulus of germanium-antimony-tellurium (GST) PCM is significantly different in the amorphous and crystalline states (Nazeer, H. *Thin films on cantilevers. PhD thesis, University of Twente (2012)*, Won, Y. et al. *Phase and thickness dependent modulus of $\text{Ge}_2\text{Sb}_2\text{Te}_5$ films down to 25 nm thickness. Appl. Phys. Lett. 100, 161905 (2012)*). It has been observed that the change in elastic properties associated with the phase change of GST increases with decreasing layer thickness.

Referring back to Figure 1, the fundamental mode of the cantilever 12 is an out-of-plane transverse vibration having a node at the root of the cantilever 12 and an anti-node at the tip. The natural frequency of a vibrating structure is given by:

$$\omega = \sqrt{\frac{k}{m}}$$

where k is the effective (Lagrangian) stiffness and m the effective mass associated with the mode of vibration. For the fundamental (out-of-plane flexural) mode, the effective stiffness of a homogenous cantilever beam is proportional to the cube of the thickness of the cantilever (in the out-of-plane direction) and the effective mass scales linearly with thickness, which means that the natural frequency is proportional to the square of the thickness of the beam. The effective stiffness is linearly proportional to Young's modulus.

- 10 In the resonator of Figure 1, when the PCM layer 12 undergoes a phase change, the stiffness contribution from the PCM layer 12 is altered, thereby changing the natural frequency of the cantilever. There may additionally be a change in the thickness of the PCM layer due to a change in density associated with the phase change. This change in thickness may contribute to a change in the effective stiffness, but the effect of this
15 on natural frequency may be secondary to the change in elastic properties.

- The change in the density of the PCM layer between amorphous and crystalline states may be associated with a change in the internal stress of the PCM layer due to the associated change in volume (depending on how the material is constrained). For a
20 cantilever beam, this may result in curvature of the beam (where the PCM layer is positioned remote from the neutral axis), but may have a relatively small effect on the resonant frequency of the fundamental mode of vibration. For structures capable of supporting tension (e.g. a membrane or bridge) the internal stress produced by phase change may act against the change in elastic properties resulting from phase change.
25 For example GST PCM may reduce in volume on transitioning to the crystalline state, which may act to increase tension in a membrane or bridge structure.

- An example cantilever, according to Figure 1, can be simulated to illustrate the change in resonant frequency that may be achieved by changing the phase of the PCM layer.
30 The natural frequencies of the system may be calculated using well known methods (for example finite element analysis). In the simulated embodiment, the mechanical layer 14 is a 1µm thick silicon layer (e.g. polysilicon, or (100) crystalline silicon, with the axis of the cantilever in the [110] crystallographic direction). The PCM layer 13 is

a GST layer, specifically $\text{Ge}_2\text{Sb}_2\text{Te}_5$. The mechanical properties assumed for the GST and Si material in this simulation are mentioned in Table 1, below.

Figure 3 shows the relationship between a ratio of the thickness t_{PCM} of the PCM layer 13 and the thickness t_{base} of the mechanical layer 14, and the frequency change resulting from tuning ($\Delta f_{\%}$) defined as the ratio of the natural frequency of the fundamental mode with the PCM layer in the crystalline state and the amorphous state. If the thickness of the PCM layer 13 is several times that of the mechanical layer 14, $\Delta f_{\%}$ approaches 50%, which is close to the theoretical limit obtainable from the change in Young's modulus between the amorphous and crystalline phase. This corresponds to the effective stiffness of the cantilever 12 being dominated by the PCM layer 13. When the thickness of the PCM layer 13 is made very small relative the thickness of the mechanical layer 14, the change in frequency resulting from the phase change becomes very small, because the effective stiffness contribution from the PCM layer is very small.

Figure 3 further shows the threshold voltage as a function of the PCM layer thickness. This is based on the assumption that there is a linear relationship between the thickness of the PCM and the voltage required to induce sufficient heating to switch the phase of the material. An average increase of 100V per micron is assumed. For a desired tuning frequency change $\Delta f_{\%}$ of 20%, a tuneable resonator may require a voltage of as much as 200V to be applied across the PCM layer.

In the embodiment simulated in Figure 3, phase change is induced by passing current through the thickness of the PCM layer 13 via electrodes (not shown in Figure 1) positioned on either side of the PCM layer 13. For example, the PCM layer 13 may be disposed between a first and second conducting layer. The mechanical layer 14 may comprise one of these conducting layers (for instance where the mechanical layer 14 is p or n doped silicon or polysilicon). Either conducting layer may comprise tungsten, titanium tungsten or titanium nitride, or any other conductor suitable for operation at the melting point of the PCM (e.g. 600°C) and for achieving a low contact resistance with the PCM.

In some embodiments, the mechanical layer may be electrically insulating (e.g. silicon nitride, or silicon oxide). In some embodiments a first electrode layer, PCM layer and

second electrode layer may be supported by the mechanical layer, with the PCM layer between the first and second layer. In some embodiments, the heating of the PCM layer may be achieved without passing current through the PCM layer. For instance, passing current through a conductor supported by the mechanical layer may result in the temperature of the PCM layer increasing. In some embodiments (for example a bridge resonator), current may be passed along the structure of the resonator (e.g. between anchoring locations), so as to heat the mechanical layer and the PCM layer supported thereby. A heater track (e.g. a serpentine track) may be defined in a conducting layer supported by the mechanical resonator, for heating the PCM. Such an arrangement may allow a relatively low voltage to provide sufficient heating of a region of the PCM to induce a phase change in that region.

Figure 4 schematically illustrates an example resonator 40 in which the resonant structure 12 is a fixed-fixed beam (or bridge). The resonator comprises a substrate 17, insulating layer 15, mechanical layer 14 and PCM layer 13. The PCM layer is disposed on, and supported by, the mechanical layer 14. The resonant structure 12 thereby comprises a composite layer comprising the mechanical layer 14 and the PCM layer 13. The resonant structure 12 bridges a recess 16, defined in the insulating layer 15 on which the mechanical layer 14 is disposed.

20

The substrate 17 may be a silicon wafer. The insulating layer 15 may be silicon oxide, or a polymeric layer such as SU8, PMMA or polyimide. The mechanical layer may be silicon, polysilicon, silicon nitride, silicon oxide, or any other suitable material. The PCM layer 13 may be GST.

25

This type of resonator 40 is sensitive to residual stresses in the layers 13, 14 comprising the resonant structure. Such residual stresses may result in tensioning of the fixed-fixed beam, which will have the result of increasing the effective stiffness of transverse vibrational modes of the resonant structure. For a high aspect ratio structure (in which length $\gg$ thickness), the effective stiffness can easily be dominated by tension arising from residual stress. Any residual stresses resulting from a phase change of the PCM layer 13 may thereby contribute significantly to frequency tuning of the resonant structure.

30

One way to increase the change in frequency in a resonator as a result of a phase change in PCM comprised as part of the resonator is to ensure that the effective stiffness of the mode of interest of the resonator is dominated by the PCM (or at least that the PCM makes a very significant contribution to the effective stiffness). This
5 may be achieved by using a very thin layer as the mechanical layer.

Materials suitable for forming atomically thin monolayers (sometimes referred to as 2D materials) such as graphene and molybdenum disulphide have recently been employed in resonator structures. The extremely thin thickness dimension provides
10 resonators that are particularly sensitive to mass and force perturbations, and which operate at reasonably high frequencies (which may be applicable to RF receivers, as oscillators or bandpass filters). Drum resonators, in which a membrane comprising a thin layer of material resonates in a transverse mode, have been previously demonstrated (*Barton, A. R., et al. High, size-dependent quality factor in an array of*
15 *graphene mechanical resonators. Nano Lett. 11 (3): 1232–6 (2011)*).

A sectional view of an example membrane type mechanical resonator is shown in Figure 5. The resonator 50 comprises a resonating structure 12, substrate 17, insulating layer 15, first mechanical layer 14, PCM layer 13 and second mechanical
20 layer 18. The resonating structure 12 is a membrane, fixed around its edges (e.g. a circular membrane), and comprises the first and second mechanical layers 14, 18, which are disposed either side of the PCM layer 13.

The substrate 17 may conveniently comprise silicon (or other materials such as glass
25 or sapphire). The insulating layer 15 may comprise silicon oxide, or may be dispensed with, for instance if there is no need for electrical insulation, or if the substrate 17 or first mechanical layer 14 are insulating. The layers 14, 13, 18 comprising the resonator structure 12 are suspended over a recess 16 defined in the insulating layer 15 (or the recess 16 may, if the insulating layer 15 is dispensed with, be defined in the
30 substrate 17).

The first and second mechanical layers 14, 18 may comprise graphene, or another material suitable for depositing in a film having a thickness of less than 100nm. In addition to being suitable for forming into very thin layers, graphene is electrically
35 conducting, which allows it to function as an electrode. The first and second

mechanical layers 14, 18 may thereby function as first and second electrode layers respectively. In an alternative embodiment, insulating layers may be used for the first and second mechanical layers 14, 18, with additional conducting layers (not shown) serving as electrodes if necessary.

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The first and second electrodes may be used to provide a current pulse through the PCM layer for changing its phase. In addition, at least one of the electrodes may be used for electrostatically driving the resonating structure to vibrate, and/or for detecting the vibration of the resonating structure. A stationary electrode may be provided adjacent to the resonating structure 12 for electrostatic transduction. Where the substrate is electrically conducting, the substrate 17 may function as the stationary electrode. Alternatively, a conducting stationary electrode may be formed on the substrate 17.

15 In addition to frequency tuning from changing the phase of the PCM layer 13, further tuning may be provided by a DC voltage bias between the stationary electrode and a moving electrode comprised as part of the resonating structure 12. The skilled person will be aware of such electrostatic tuning mechanisms, which are well known in the context of MEMS resonators. The combination of electrostatic tuning and tuning by
20 changing the phase of a material that contributes to the effective stiffness of the resonator are complementary and enable a broad range of tuning. The phase change based tuning may be stable, and not require an electrical bias to maintain. The electrostatic tuning may be capable of fine adjustment, for example to compensate for temperature changes of the resonator. The phase change frequency tuning may be used
25 to select a different band of operation by making a large change in frequency.

Referring to Figure 6 an example resonator 60 is shown. The resonator 60 comprises an insulating layer 15 and first and second graphene mechanical layers 14, 18, disposed on either side of a GST PCM layer 13. The first and second mechanical
30 layers 14, 18 act as first and second electrodes respectively, which may be used to apply a current pulse from phase changing circuit 61, so as to change the phase of the PCM layer 13. The resonating structure 12 is in the form of a circular membrane resonator.

Figures 7 and 8 show simulated performance of the embodiment of Figure 6. The mechanical properties employed in the simulation are shown below in Table 1. The graphene layers each comprise an atomic monolayer (i.e. a single graphene sheet).

Possion ratio $\text{Ge}_2\text{Sb}_2\text{Te}_5$, V_{gst}	0.3
Young's modulus amorphous $\text{Ge}_2\text{Sb}_2\text{Te}_5$, E_{amo}	9 GPa
Young's modulus crystalline $\text{Ge}_2\text{Sb}_2\text{Te}_5$, E_{cry} t represents the thickness of the PCM film.	$t = 10 \text{ nm}$, $E_{cry} = 54 \text{ GPa}$ $t = 15 \text{ nm}$, $E_{cry} = 50 \text{ GPa}$ $t = 20 \text{ nm}$, $E_{cry} = 47 \text{ GPa}$ $t = 30 \text{ nm}$, $E_{cry} = 41 \text{ GPa}$ $t = 40 \text{ nm}$, $E_{cry} = 38 \text{ GPa}$ $t = 50 \text{ nm}$, $E_{cry} = 35 \text{ GPa}$
Density amorphous $\text{Ge}_2\text{Sb}_2\text{Te}_5$, d_{amo}	5870 Kg/m ³
Density crystalline $\text{Ge}_2\text{Sb}_2\text{Te}_5$, d_{cry}	6270 Kg/m ³
Young's modulus graphene, E_{gra}	1000 GPa
Poisson ratio graphene, V_{gra}	0.17
Density graphene, d_{gra}	2200 Kg/m ³
Density Si, d_{Si}	2329 Kg/m ³
Young's modulus Si, E_{Si}	170 GPa
Poisson ratio Si, V_{Si}	0.28

5

Table 1: Mechanical properties

Figure 7 shows a graph 70 illustrating the relationship between the thickness of the PCM layer 13 and the resonant frequency of the fundamental transverse membrane mode (having a single anti-node in the centre of the membrane), for a range of membrane radii and for the GST PCM layer 13 in a crystalline state and in an amorphous state. Lines 71 and 72 respectively correspond with crystalline and amorphous states for a membrane radius of 100nm, lines 73 and 74 with crystalline and amorphous states for a membrane radius of 200nm, lines 75 and 76 with crystalline and amorphous states for a membrane radius of 400nm, and lines 77 and 78 with crystalline and amorphous states for a membrane radius of 1000nm. The GSM (global system for mobile communications) band is marked on the graph. A

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mechanical resonator operable at frequencies within the GSM band is desirable for telecommunications applications (e.g. as a local oscillator or bandpass filter).

Figure 8 shows a graph 80 illustrating the relationship between the thickness of the PCM layer 13 and change in natural frequency of the fundamental transverse membrane mode) for a range of membrane radii. Lines 81, 82, 83, and 84 respectively correspond with a membrane radius of 100nm, 200nm, 400nm, and 1000nm.

A membrane radius with less than 200nm radius may be appropriate for the GSM band, as shown by Figure 7. Referring to Figure 8, a relatively small thickness of PCM (e.g. below 15nm) may achieve a significant tuning effect, of around 15-20% for a membrane with radius 200nm, or around 50-30% for a membrane with radius 100nm. A thin PCM layer may also result in a smaller threshold voltage for switching the phase of the PCM.

The small lateral dimension (e.g. less than 200nm) is encouraging, because it means that producing a device is more straightforward. Active devices with large dimensions (e.g. above 1µm) may result in the some PCMs not entirely switching from the amorphous to the crystalline state, due to the creation of sort circuit filamentation effects. A tiny conducting path may be created, which effectively short circuits the electrodes and prevents further material being transformed in the crystalline state. The creation of such a filament is more likely in a larger device. For devices with dimensions below 300nm this is not a significant problem.

Referring to Figure 10 an example process flow 110 for manufacturing a resonator are shown in outline form. In a first step 101, a recess may be formed in a fixed layer of a substrate (e.g. a silicon oxide layer). The recess may be formed by lithography and etching (e.g. e-beam lithography and wet or vapour phase HF etching). A graphene layer may be prepared on a carrier (e.g. a copper foil), for example by chemical vapour deposition. In a second step 102, the graphene layer may be transferred onto substrate layer comprising the recess. In a third step 103, a phase change material (e.g. GST) then be deposited on the graphene layer over the recess, for example by sputtering or pulsed laser deposition. In a fourth step 104, a further graphene layer (which may also be formed by CVD on a carrier) may then be transferred onto the PCM layer to encapsulate it between the two graphene layers. This last step may be

performed immediately after deposition of the PCM layer so as to prevent degradation thereof (e.g. by oxidation).

Figure 9 shows an example of a RF (radio frequency) receiver architecture comprising a resonator according to an embodiment. The RF receiver 90 comprises an antenna 91, low noise amplifier (LNA) 92, first bandpass filter 93, mixer 95, second bandpass filter 94 and local oscillator 96. The antenna 91 is configured to receive a baseband RF signal. The antenna 91 provides the baseband RF signal to the LNA 92, which amplifies the signal. The first bandpass filter 93 filters unwanted frequencies from the output of the LNA 92, and provides a filtered signal to the mixer 95. The mixer 95 mixes a local oscillator signal, provided by the local oscillator 96, with the filtered baseband signal to produce a signal at an intermediate frequency (IF). The IF signal is subsequently filtered by the second bandpass filter 94, before being provided to further signal processing elements, which may demodulate the signal.

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The first bandpass filter 93 and/or the second bandpass filter 94 may comprise a mechanical resonator according to an embodiment. The local oscillator 96 may comprise a mechanical resonator according to an embodiment.

In some embodiments, a partial phase change of the PCM may be effected, for example by transforming only a sub-region of the PCM comprised in the resonating structure. Control over the amount of PCM that changes phase may be used to provide a greater number or range of selectable frequencies that may be obtained by phase change frequency tuning. A plurality of electrodes and/or electrical tracks may be provided for phase changing distinct regions of the PCM. In alternative embodiments, a sub-threshold voltage may be used to effect less than total phase change.

The crystalline fraction of the PCM is a function of temperature and time (in accordance with the Johnson-Mehl-Avrami theory). Controlling the duration and amount of heating of the PCM can thereby control the crystalline fraction of the PCM, enabling finely graduated control of the frequency of the mechanical resonator.

The resonator may comprise an electrical circuit for at least one of: changing the phase of the PCM, driving the vibration mode, sensing the vibration mode, electrostatically tuning the resonant structure. The resonator may comprise optical

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means for driving the vibration mode, sensing the vibration mode and changing the phase of the PCM. Laser power may be used to heat the PCM, thereby changing its phase.

5 Figure 11 shows a radio frequency switch 200. The switch 200 comprises a cantilever comprising a first mechanical layer 14 and a PCM layer 13. The PCM layer 13 may comprise or consist of any of the PCM material layers described above with reference to a resonator, and the mechanical layer 14 likewise may comprise or consist of any of the materials or layers described above with reference to resonators.

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The change in phase of the phase change material layer 13 results in a change in the internal stress (or strain) of that layer, which causes the cantilever to curve, because the phase change material layer 13 is offset from the neutral axis of the cantilever. The operating principles of such an arrangement are similar to a bimorph cantilever
15 that is actuated using a piezoelectric layer. The deflection of such a beam in response to the phase change can readily be modelled by adapting the approach of Smits (*Smits, Jan G., Susan I. Dalke, and Thomas K. Cooney. "The constituent equations of piezoelectric bimorphs." Sensors and Actuators A: Physical 28.1 (1991): 41-61*), substituting the strain resulting from an applied field with the strain resulting from the
20 change of phase of the PCM layer 13.

Figure 11 shows the cantilever in a first position 13, 14 in which the mechanical layer 14 is in close proximity to fixed conducting elements 201, 202. The first position may correspond with the PCM layer 13 being in an amorphous state. When the PCM layer
25 13 is subjected to a phase change resulting in the PCM layer 13 at least partially being in a crystalline state, an associated decrease in the volume of the PCM layer will result in the cantilever curving upwards. Figure 11 shows an example second position 13', 14' in which the mechanical layer 14 and PCM layer 13 are curved due to a phase transition of the PCM material.

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Importantly, the position of the cantilever is maintained in the selected position without power consumption, because the PCM layer is stable in either state under normal conditions. This is an important advantage of a PCM layer over a piezoelectric layer. A partial phase change (i.e. a phase change in only some of the PCM layer 13)
35 may be used to effect a smaller movement of the cantilever. The position can be

adjusted with a high degree of resolution by controlling the amount and duration of heating applied to the PCM layer 13.

5 The cantilever is depicted schematically with an anchor at one end. In a practical device the cantilever may be fixed to the underlying substrate (not shown in Figure 11).

10 The fixed conducting elements 201, 202 form a coplanar waveguide, in which the central conducting element 201 carries a radio frequency signal. The mechanical layer 14 comprises an electrically conductive material, such as graphene or polysilicon. In the first position, the proximity of the conductive mechanical layer 14 to the central conducting element 201 capacitively couples with the mechanical layer 14 to provide an electrical path between the mechanical layer 14 and the central conducting element 201. In the second position, the increased gap between the mechanical layer 14' and
15 the central conducting element 201 provides electrical isolation between the mechanical layer 14' and the central conducting element.

The mechanical layer 14, 14' may be configured to shunt a signal from the central conducting element 201 to ground when the switch is in the first position, and to allow
20 the signal to pass when the switch is in the second position.

In alternative embodiments, the switch may make physical contact with an electrical conductor, and form an ohmic (resistive) contact directly between a conducting portion of the switch and a fixed conductor. In some embodiments the switch may
25 provide a conducting path between two isolated fixed electrical conductors, in one position, while maintaining electrical isolation between the two isolated fixed conductors in a second position.

30 It will be appreciated that an actuator including a PCM layer or portion can be applied in a wide range of applications, for example to actuate an optical component such as a variable optical attenuator, spatial light modulator, etalon or moving mirror.

The skilled person will appreciate that a number of other variations are possible that have not been described in detail. Although a number of example embodiments have

been described, these should not be construed as limiting the scope of the invention, which is defined by the appended claims.

CLAIMS

1. A mechanical resonator having a resonant structure, wherein the resonant structure comprises a first mechanical layer supporting a phase change material, the phase change material having a first solid phase and a second, different, solid phase, wherein a natural frequency of a vibration mode of the resonant structure varies in response to changing the phase of the phase change material from the first solid phase to the second solid phase.
2. The mechanical resonator of claim 1, wherein the phase change material comprises germanium-antimony-tellurium.
3. The mechanical resonator of claim 1 or 2, wherein the resonant structure comprises a second mechanical layer, wherein:
 - the phase change material comprises a phase change material layer between the first and second mechanical layers, and
 - at least one of the first and second mechanical layers is a layer with a thickness of less than 30nm, such as graphene.
4. The mechanical resonator of claim 1 or 2, wherein the first mechanical layer comprises graphene.
5. The mechanical resonator of any of claim 1, 2 or 4, further comprising a second mechanical layer, wherein the phase change material is comprised of a phase change material layer between the first and second mechanical layers.
6. The mechanical resonator of claim 3 or claim 5, wherein the first and second mechanical layers comprise electrically conductive material, the first and second mechanical layers being configured to change the phase of the phase change material by passing a current through the phase change material via the first and second mechanical layers.
7. The mechanical resonator of any preceding claim, comprising a phase changing means that includes an electrically conducting track adjacent to the phase change

material, wherein the electrically conducting track is operable to change the phase of the phase change material by joule heating of the conducting track.

8. The mechanical resonator of any preceding claim, further comprising a stationary electrode adjacent to the resonant structure, wherein the resonant structure comprises a moveable electrode, the stationary and moveable electrodes being configured for electrostatic tuning of a resonant frequency of the resonant structure.

9. The mechanical resonator of any preceding claim, wherein the first mechanical layer has a thickness of less than 100nm.

10. The mechanical resonator of claim 9, wherein the first mechanical layer has a thickness of less than 30nm.

11. The mechanical resonator of any preceding claim, wherein the resonant structure comprises: a membrane, a cantilever, a bridge, a free-free beam, a ring, a disk, or a tuning fork.

12. The mechanical resonator of any preceding claim, wherein the resonant structure comprises a membrane, and the vibration mode is a transverse membrane vibration mode.

13. The mechanical resonator of claim 12, wherein a lateral dimension of the membrane is less than 1 micron.

14. The mechanical resonator of any preceding claim, further comprising an excitation means for driving the vibration mode of the resonant structure.

15. The mechanical resonator of claim 14, wherein the excitation means comprises a laser for opto-mechanically driving the resonator.

16. The mechanical resonator of any preceding claim, further comprising sensing means for detecting the vibration mode of the resonant structure.

17. The mechanical resonator of claim 16, wherein the sensing means comprises a light sensing element for optically detecting the vibration of the resonant structure.

18. The mechanical resonator of any preceding claim, wherein the first mechanical resonator comprises a piezoresistive element, arranged to change resistance as a consequence of a displacement corresponding with the vibration mode.

19. An oscillator comprising a mechanical resonator according to any preceding claim or an array of mechanical resonators according to any preceding claim.

20. A bandpass filter comprising a mechanical resonator according to any preceding claim or an array of mechanical resonators according to any preceding claim.

21. A mobile communication device comprising the oscillator of claim 18 or the bandpass filter of claim 20.

22. A method of making a mechanical resonator, comprising the steps of:
forming a recess in a fixed layer of a substrate;
transferring a first graphene layer onto the substrate;
depositing a phase change material on the first graphene layer; and
transferring a second graphene layer onto the phase change material.

23. The method of claim 22, wherein the recesses in the fixed layer are formed before the first layer is transferred onto the substrate.

24. The method of any of claim 22 or 23, further comprising a step of depositing the first or second graphene layer by chemical vapour deposition.

25. The method of any of claims 22 to 24, wherein the step of depositing the phase change material comprises sputtering the phase change material.

26. The method of any of claims 22 to 25, wherein the phase change material comprises germanium-antimony-tellurium.

27. An actuator comprising a cantilever, the cantilever comprising a first mechanical layer supporting a phase change material, the phase change material having a first solid phase and a second, different, solid phase, wherein the cantilever is displaced in response to changing the phase of the phase change material from the first solid phase to the second solid phase.

28. A radio frequency switch, comprising the actuator of claim 27.

29. The radio frequency switch of claim 28, wherein the cantilever is displaced from a first position to a second position in response to changing the phase of the phase change material, and the cantilever comprises a conducting element that provides an electrical path between two separated conductors in a first position, and which provides electrical isolation between two separated conductors in the second position.

30. The radio frequency switch of claim 29, wherein the electrical path provided by the conducting element is by ohmic contact between the conducting element and at least one of the separated conductors.

31. The radio frequency switch of claim 29, wherein the electrical path provided by the conducting element is by capacitive coupling between the conducting element and at least one of the separated conductors.

32. The radio frequency switch of any of claims 28 to 31, wherein at least one of the separated conductors is part of a coplanar waveguide.

33. An apparatus or device substantially as described herein, with reference to the accompanying drawings.

34. A method substantially as described herein, with reference to the accompanying drawings.

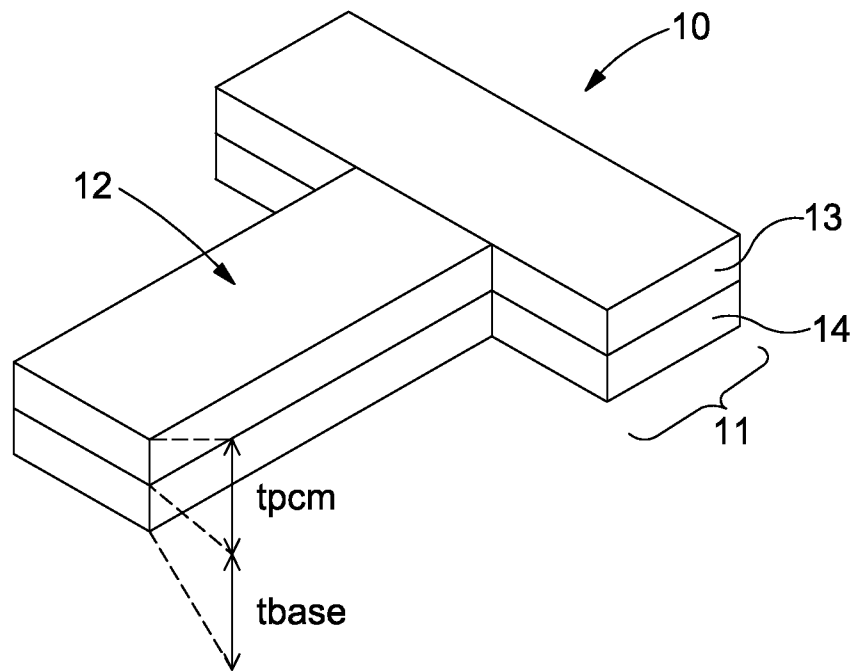


Figure 1

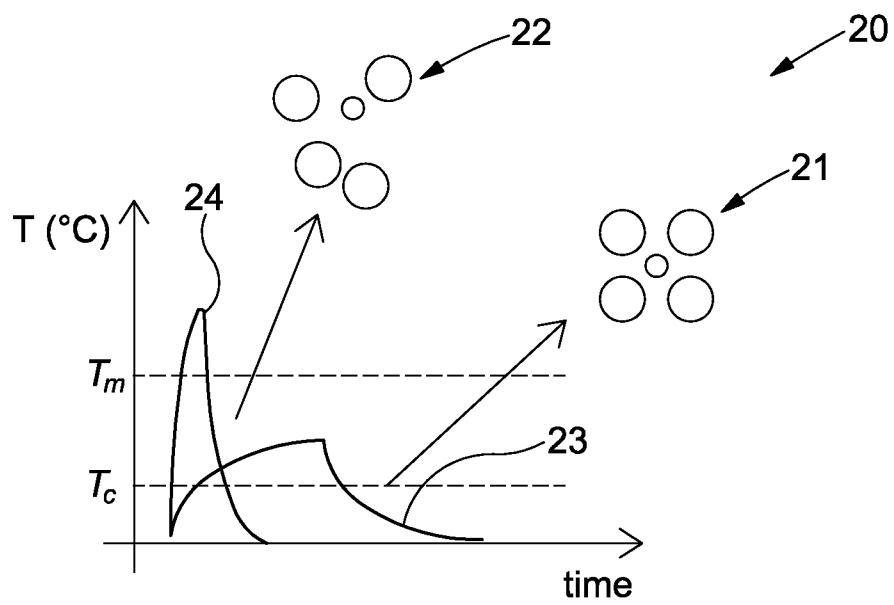


Figure 2

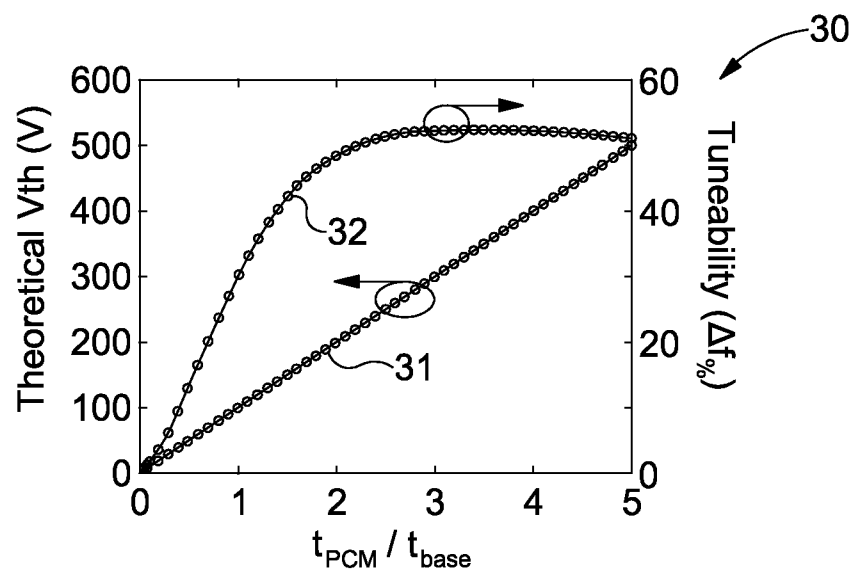


Figure 3

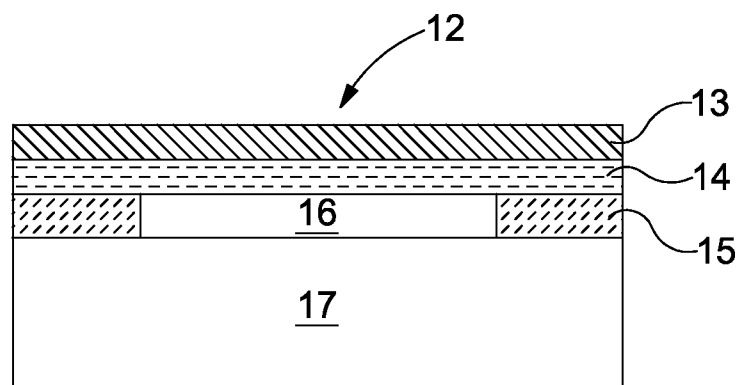


Figure 4

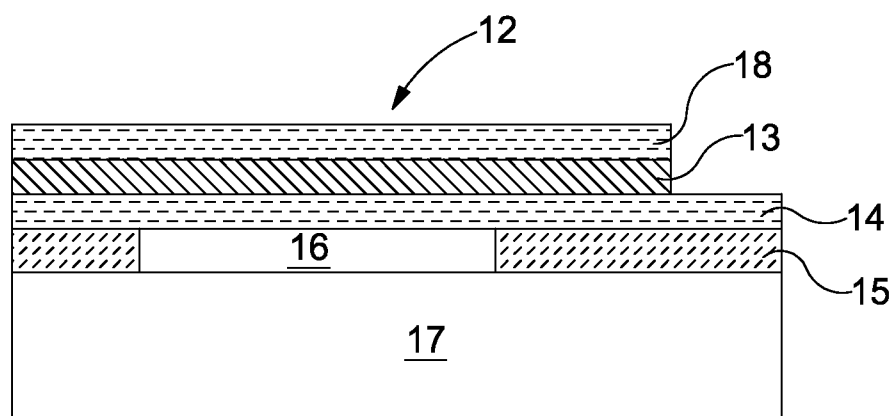


Figure 5

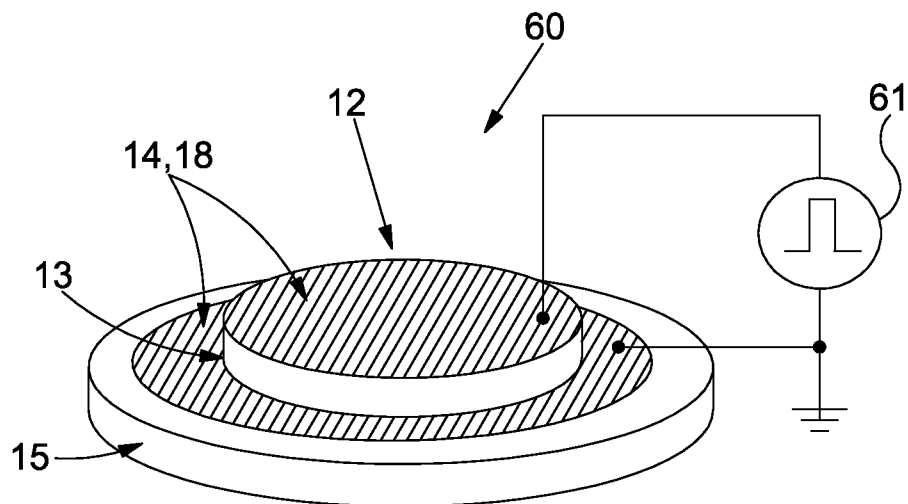


Figure 6

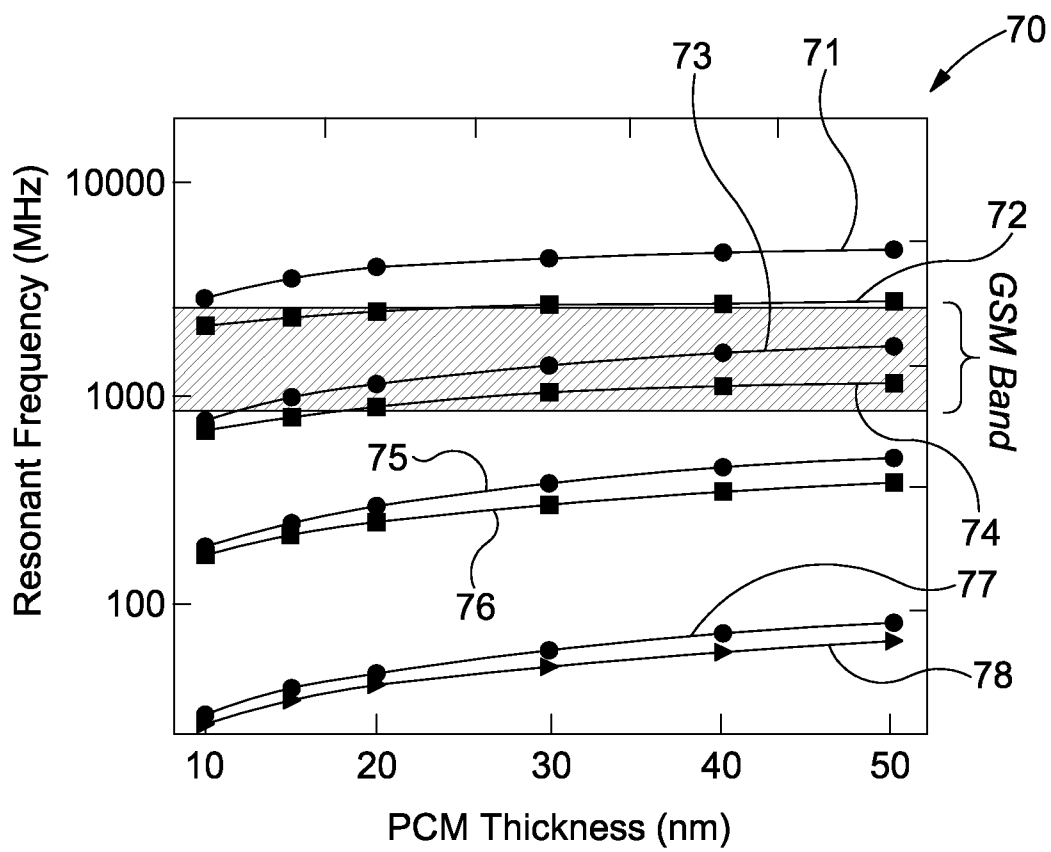


Figure 7

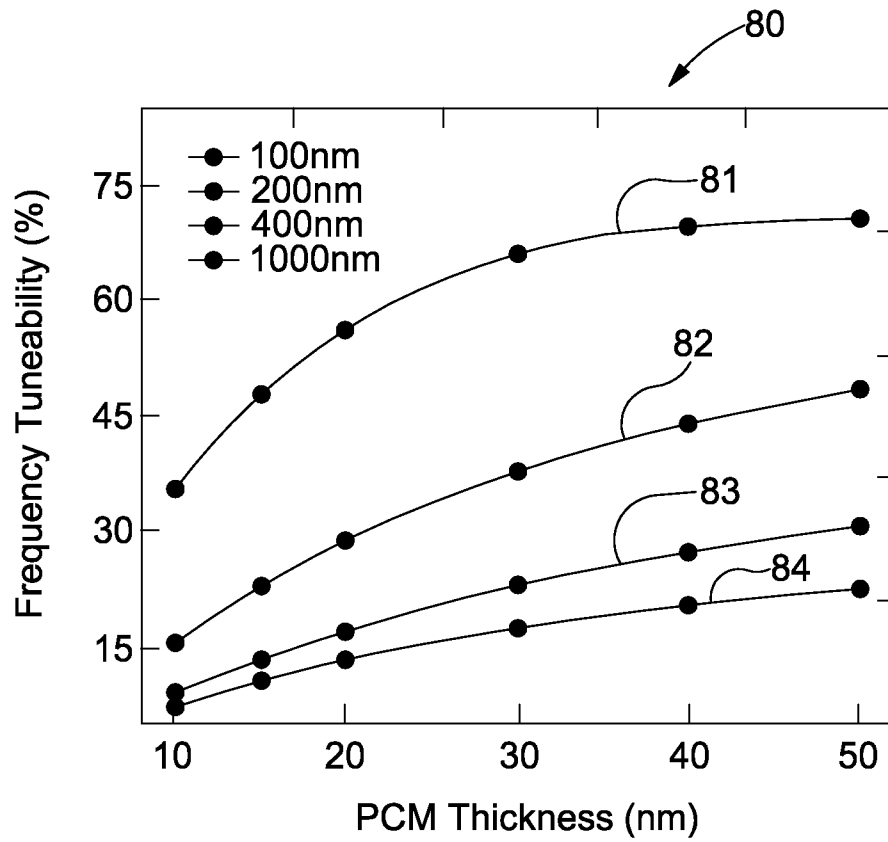


Figure 8

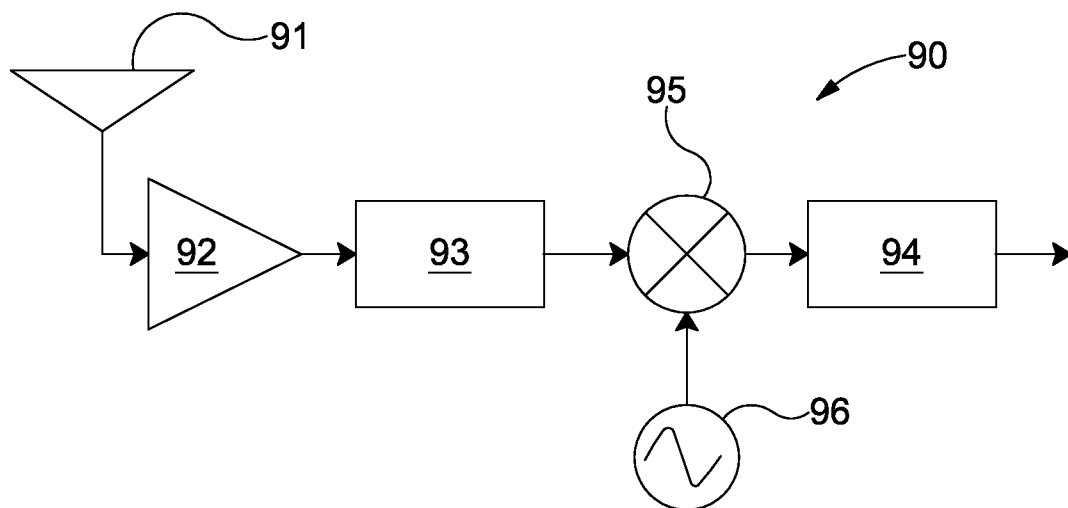


Figure 9

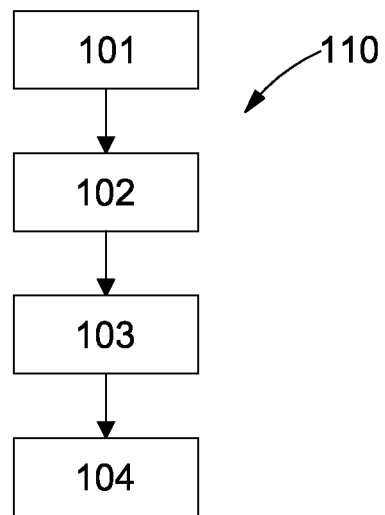


Figure 10

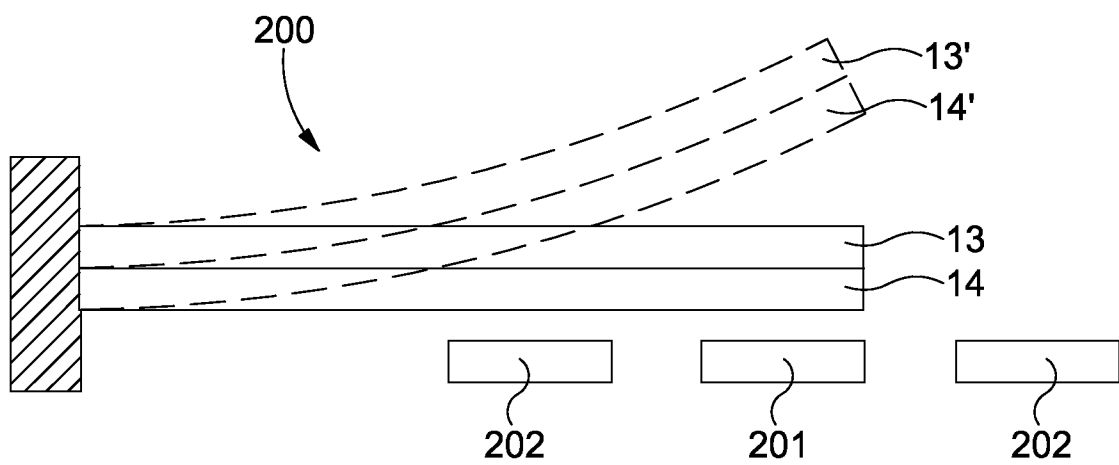


Figure 11

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2016/050802

A. CLASSIFICATION OF SUBJECT MATTER

INV. B81B3/00 H03H9/02 H03H9/24
ADD.

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)

B81B H03H

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

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

EPO-Internal, WPI Data, COMPENDEX, INSPEC, IBM-TDB

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	NICOLA MANCA ET AL: "Programmable Mechanical Resonances in MEMS by Localized Joule Heating of Phase Change Materials", ADVANCED MATERIALS, vol. 25, no. 44, 1 November 2013 (2013-11-01), pages 6430-6435, XP055275778, DE ISSN: 0935-9648, DOI: 10.1002/adma.201302087 right-hand column, lines 4-18 - page 6430 ----- -/--	1,2,4, 7-21



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

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

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

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search

27 May 2016

Date of mailing of the international search report

10/08/2016

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
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Fax: (+31-70) 340-3016

Authorized officer

Radomirescu, B-M

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2016/050802

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	HUMMEL GWENDOLYN ET AL: "Phase change material programmable vias for switching and reconfiguration of Aluminum Nitride piezoelectric MEMS resonators", 2014 IEEE INTERNATIONAL FREQUENCY CONTROL SYMPOSIUM (FCS), IEEE, 19 May 2014 (2014-05-19), pages 1-3, XP032623346, DOI: 10.1109/FCS.2014.6859996 ch. I-II; figures 1,2	1,2,4, 7-21
X	----- WON YOONJIN ET AL: "Phase and thickness dependent modulus of GeSbTefilms down to 25 nm thickness", APPLIED PHYSICS LETTERS, A I P PUBLISHING LLC, US, vol. 100, no. 16, 16 April 2012 (2012-04-16), pages 161905-161905, XP012155646, ISSN: 0003-6951, DOI: 10.1063/1.3699227 [retrieved on 2012-04-18] figure 1	1,2,4, 7-21
A	----- ROBERT A. BARTON ET AL: "High, Size-Dependent Quality Factor in an Array of Graphene Mechanical Resonators", NANO LETTERS, vol. 11, no. 3, 9 March 2011 (2011-03-09), pages 1232-1236, XP055274586, US ISSN: 1530-6984, DOI: 10.1021/nl1042227 abstract	1,2,4, 7-21
A	----- US 2013/062104 A1 (CRAIGHEAD HAROLD G [US] ET AL) 14 March 2013 (2013-03-14) figures 1-4	1,2,4, 7-21
A	----- US 2011/279188 A1 (SHIN JEA SHIK [KR] ET AL) 17 November 2011 (2011-11-17) figures 3-5	1,2,4, 7-21

INTERNATIONAL SEARCH REPORT

International application No.
PCT/GB2016/050802

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☒ Claims Nos.: 33, 34
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
see FURTHER INFORMATION sheet PCT/ISA/210
3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of Item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:
1, 2, 4, 7-21

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

Continuation of Box II.2

Claims Nos.: 33, 34

Independent claims 33, 34 do not comply with the requirements of Rule 6.2(a) PCT and their subject-matter cannot be clearly, unambiguously delimited from the prior art nor from the subject-matter of the other claims to such an extent that their search cannot be meaningfully performed.

The above objected deficiency is of such nature that their subject-matter cannot be clearly delimited and assigned to one of the inventions detailed in the annexes of the present search report.

The applicant's attention is drawn to the fact that claims relating to inventions in respect of which no international search report has been established need not be the subject of an international preliminary examination (Rule 66.1(e) PCT). The applicant is advised that the EPO policy when acting as an International Preliminary Examining Authority is normally not to carry out a preliminary examination on matter which has not been searched. This is the case irrespective of whether or not the claims are amended following receipt of the search report or during any Chapter II procedure. If the application proceeds into the regional phase before the EPO, the applicant is reminded that a search may be carried out during examination before the EPO (see EPO Guidelines C-IV, 7.2), should the problems which led to the Article 17(2) declaration be overcome.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. claims: 1, 2, 4, 7-21

Tunable mechanical resonator

2. claims: 3, 5, 6, 22-26

Tunable mechanical resonator

3. claims: 27-32

Tunable mechanical actuator

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/GB2016/050802

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2013062104 A1	14-03-2013	NONE	

US 2011279188 A1	17-11-2011	KR 20110124590 A	17-11-2011
		US 2011279188 A1	17-11-2011
