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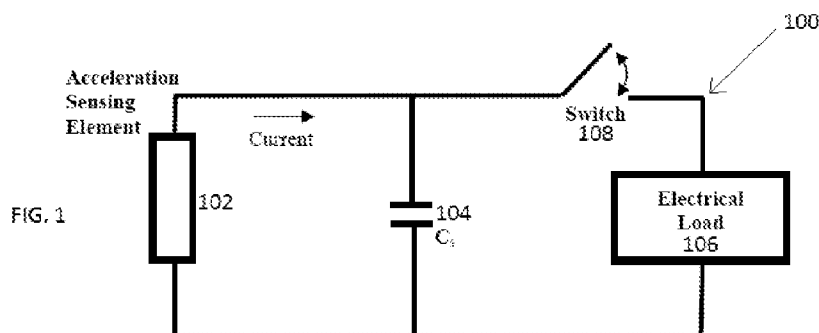
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(54) **Title:** A SELF-POWERED ACCELERATION SENSING DEVICE

(57) **Abstract:** Disclosed is a self-powered acceleration sensing device. The device includes an acceleration sensing element for converting vibration into electrical energy, and a charge accumulator electrically connected to the acceleration sensing element to accumulate at least a portion of the electrical energy converted from vibration by the acceleration sensing element over a period of time. The device further includes a load to be powered by discharge of the portion of the electrical energy from the charge accumulator and being capable of producing an output that is directly observable by an operator, and a switch for controlling discharge of electrical energy from the charge accumulator to the load. The switch performs switching between a first condition in which current is substantially prevented from passing through the load, and a second condition in which the portion of the electrical energy is discharged from the accumulator to the load. Moreover, switching is controlled by an amount of energy accumulated in the charge accumulator.



A SELF-POWERED ACCELERATION SENSING DEVICE

TECHNICAL FIELD

The present disclosure relates to acceleration or vibration sensing devices. In particular, the present disclosure relates to, but is not limited to, acceleration or vibration sensing devices employing a high impedance sensing element, such as a piezoelectric material.

BACKGROUND

Acceleration or vibration sensing devices, or “accelerometers”, have been used to monitor the structural health of buildings, equipment aging, the condition of automobile engines and even biorhythmic behaviour.

The sensed vibrations trigger a response, or generate a signal, that is observable or perceivable by an operator. Such a response or signal may be displayed to the operator, result in an audible alarm or visible light can be recorded.

Due to the very low current generated by a typical acceleration sensing element, they are usually unsuitable for powering displays and components by which the response or signal is made evident to the operator. This is particularly the case since many displays, speakers and the like, by which an operator can observe a signal, have much higher power requirements than the power output of the acceleration sensing element, and also have high leakage current – so it is difficult to store charge in circuits containing such display and speaker devices that are powered only by the acceleration sensing element. As such, the display or speaker by which the response or signal is made observable to the operator is typically powered by an external power source.

In relying on an external power source, such devices similarly rely on the external power source remaining operational, or even switched on. Where the external power source is not operational or is switched off, it may no longer be possible for the device to make the requisite response or signal observable to the operator. Thus

the operation of the device is reliant on the availability of the external power source, which often has a much lower longevity than the accelerometer.

To remedy this issue, some prior art devices purport to be powered by the electrical
5 energy generated during vibration sensing. For example, the piezoelectric acceleration sensing element or material of a piezoelectric accelerometer will generate a minute electric under vibration. That minute current can be used to power other components of the accelerometer.

10 Typically, the minute current of the acceleration sensing element is used in prior art to power an ultra-low power, low current-leakage radio-frequency (RF) transmitter the signal from which is received by a RF receiver incorporating the display for conveying the sensing information is incorporated. While the RF transmitter may be powered by electrical charge from the piezoelectric material, the RF receiver
15 including the display is powered by an external power source. Thus the system still relies on the operational status of an external power source and is not entirely self-powered.

The reason for using RF transmitters is the low leakage current and ultra-low power
20 operational requirements. Other devices, such as light-emitting diodes (LEDs) and buzzers, have traditionally not been useable since they have high leakage current. In other words, electrical energy generated by the piezoelectric sensing element will dissipate through an LED or buzzer without reaching the threshold electrical energy required for proper operation of the load, even where a charge accumulator is
25 incorporated into the circuit. For this reason, devices such as LEDs and buzzers that enable an operator to observe a response or signal directly from the accelerometer are thought to be unworkable in devices powered by the electrical energy produced by the accelerometer under vibration.

30 It is desirable that there be provided a fully self-powered acceleration sensing device or an accelerometer driven solely by the acceleration sensing element, without

assistance from any other power source of energy harvester, and that can provide a response or signal observable to an operator.

SUMMARY

5 The present disclosure provides a self-powered acceleration sensing device comprising:

an acceleration sensing element for converting vibration into electrical energy;

10 a charge accumulator electrically connected to the acceleration sensing element to accumulate at least a portion of the electrical energy converted from vibration by the acceleration sensing element over a period of time;

a load to be powered by discharge of the portion of the electrical energy from the charge accumulator and being capable of producing an output that is directly observable by an operator; and

15 a switch for controlling discharge of electrical energy from the charge accumulator to the load,

whereby the switch performs switching between a first condition in which current is substantially prevented from passing through the load, and a second condition in which the portion of the electrical energy is discharged from the accumulator to the load; and

20 switching is controlled by an amount of energy accumulated in the charge accumulator.

Advantageously, the switch can provide an ultra-sharp, non-linear switching function to connect the load with the charge accumulator, and thereby substantially avoid current leakage through the load during accumulation of electrical energy in the charge accumulator. In this regard, the switch includes a non-linear switching element, being an element the output of which is not proportional to its input. Instead, while the output of the non-linear switching element may change slightly with changes in input, the output experiences a much sharper, larger change at around the triggering level of the switching element (i.e. when it turns on).

BRIEF DESCRIPTION OF THE DRAWINGS

Some embodiments of the present invention will now be described by way of non-limiting example only with reference to the accompanying drawings in which:

- 5 FIG. 1 shows an illustrative generalised schematic diagram of a self-powered sensing device in accordance with the present invention;

FIG. 2 shows an embodiment of the present invention incorporating an LED as the electrical load;

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FIG. 3 shows an embodiment of the present invention incorporating a buzzer as the electrical load;

- FIG. 4 shows an embodiment of the present invention incorporating a transistor-based switch consisting of a single N-MOSFET biased at the gate terminal by a voltage divider comprising two capacitors;
- 15

FIG. 5 shows an embodiment of the present invention employing a transistor-based switch comprising a cascading transistor pair;

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FIG. 6 shows an embodiment of the present invention employing a switch comprising a cascading transistor pair with a capacitor at the gate of the second transistor in the cascade;

- FIG. 7 shows an embodiment of the present invention employing a transistor-based switch comprising multiple cascading transistors for multi-stage activation of the switch;
- 25

FIG. 8 shows the circuit of FIG. 1 employing a half-wave rectifier;

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FIG. 9 shows a half-wave rectified AC waveform;

FIG. 10 shows the circuit of FIG. 1 employing a full-wave rectifier;

FIG. 11 shows a full-wave rectified AC waveform;

- 5 FIG. 12 shows the circuit of FIG. 1 employing a full-wave, voltage-doubler rectifier circuit;

FIG. 13 is a schematic representation of a self-powered accelerometer of the present invention, employing a switch comprising cascading transistors and an LED as the
10 load;

FIG. 14 shows the switching profile of the end transistor of the switch of the circuit of FIG. 13;

- 15 FIG. 15 shows the voltage profile across the charge-storage capacitor of the circuit of FIG. 13, under charging action of the acceleration sensing element and discharging action through the LED;

FIG. 16 shows the time interval between successive discharge actions and thus the
20 time interval between successive flashes of the LED of the circuit of FIG. 13, exhibiting an approximately inverse-linear relationship with the acceleration experienced by the acceleration sensing element;

FIG. 17 is a schematic representation of a self-powered accelerometer of the present invention, employing a switch comprising cascading transistors and a buzzer as the
25 load;

FIG. 18 shows the voltage profile across the charge-storage capacitor of the circuit of FIG. 17, under charging action of the acceleration-sensing element and discharging
30 action through the buzzer; and

FIG. 19 shows the time interval between successive discharge actions and thus the time interval between successive beeps from the buzzer of the circuit of FIG. 17, illustrating an approximately inverse-linear relationship with the acceleration experienced by the circuit.

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DETAILED DESCRIPTION

FIG. 1 shows a generalised schematic diagram of a self-powered acceleration sensing device or accelerometer 100. The device 100 includes a vibration or acceleration sensing element 102, a charge accumulator 104, a load 106 – hereinafter an
10 ‘electrical load’ which will be understood to encompass electric and electronic loads compatible with the present disclosure – and a switch 108. The accelerometer 100 permits accumulation of electrical energy or charge generated by the acceleration sensing element 102 in response to the sensed vibration or acceleration, and the dissipation of that accumulated electrical energy via the switch 108 into the load 106
15 for generating an observable signal indicative of the sensing information. The switch is normally-open (i.e. in a first, or OFF, condition) so as to electrically isolate the electrical load 106 from the charge accumulator 104 for allowing the electrical energy or charge to build up in the charge accumulator 104, but closes (i.e. moves to a second, or ON, condition) autonomously for discharging the built-up electrical
20 energy or charge into the electrical load 106 when the built-up electrical energy or charge reaches a sufficient level to power up the electrical load 106 generating the indicative signal.

Acceleration sensing elements can convert vibrational mechanical energy into
25 electrical energy. In the present case, the acceleration sensing element is solely responsible for providing the electrical energy to power the entire sensing platform or circuit as shown in FIG. 1 and other circuits designed in accordance with the present teachings. The electrical energy thus serves two purposes: one, it powers the sensing platform; and two, it provides a sensing signal indicative of the vibration
30 or acceleration experienced by the acceleration sensing element.

The sensing signal may indicate the presence and magnitude or intensity of vibrations. The magnitude or electrical energy of the sensing signal may also be correlated to, such as proportional to the magnitude of the vibrations, or the magnitude of acceleration of the vibrations. The magnitude or electrical energy of the sensing signal may also be correlated to, such as proportional to the frequency of the vibrations.

Due to the periodic or alternating nature of vibrational motion, the sensing signal or electrical energy produced by the acceleration sensing element 102 may comprise an alternating current (AC) signal. It may alternatively comprise a direct current (DC) signal, though this is less common.

The acceleration sensing element 102 may have a high electrical impedance, for example, comprising a piezoelectric material, such as a piezoelectric ceramic, polymer, or crystal, that generates electric current under vibration. The piezoelectric material is dielectric, and may comprise materials such as piezoelectric ceramics such as Lead Zirconate Titanate (PZT), a piezoelectric crystal such as quartz, a solid solution of Lead Nickel Niobate (PNN), Lead Zinc Niobate (PZN), Lead Magnesium Niobate (PMN), Lead Zirconate (PZ) and Lead Titanate (PT), lead-free piezoelectric materials such as Potassium Sodium Niobate (KNN), and/or piezoelectric polymers such as Poly(vinylidene fluoride-co-trifluoroethylene) P(VDF-TrFE) or Polyvinylidene Fluoride (PVDF). Due to the interaction between the charge accumulator and the switch, as discussed below, the piezoelectric sensing element need only produce a very small electrical charge in order to result in accumulation over time of a charge sufficient to drive the load.

The acceleration sensing element 102 may take various configurations depending on the application in which the device 100 is to be used. For example, the acceleration sensing element 102 may comprise a piezoelectric cantilever beam. The cantilever beam may have a fixed end attached to the vibrating surface and a free end attached to a proof mass. The acceleration sensing element 102 may alternatively comprise a piezoelectric diaphragm structure with opposed fixed ends and a proof mass at a

point of the diaphragm between the two ends – for example the centre. In each case, vibration of the device 100 will result in displacement of the proof mass relative to the fixed end or ends of the acceleration sensing element 102, thereby inducing mechanical strain on the piezoelectric member, resulting in generation of electrical energy.

The acceleration sensing element 102 may instead comprise a micro-electromechanical system (MEMS) having a micro-machined piezoelectric sensing element using a piezoelectric thin film. The microstructure of the film may take the form of a cantilever or diaphragm as discussed above.

As a further alternative, the acceleration sensing element may comprise top and bottom sandwich electrodes with the piezoelectric material disposed therebetween. In this case, the polarisation of the piezoelectric material will be perpendicular to the plane of the sandwich electrodes so that it passes through those electrodes. The acceleration sensing element 102 may instead be fabricated with in-plane electrodes, thereby warranting the polarization of the piezoelectric material to be parallel to, or co-planar with, the plane in which lie the electrodes.

While each of the described embodiments of the acceleration sensing element 102 includes a piezoelectric element, it will be appreciated that other types of element may be used in particular circumstances, such as a gyroscope and magnet arrangement, provided the sensing element can convert its motion into an electrical charge.

The charge accumulator 104 is electrically connected to the acceleration sensing element 102. The charge accumulator is also electrically connected to the switch 108. In the arrangement shown, the charge accumulator 104 is connected across the terminals of the acceleration sensing element 102. The switch 108 is arranged to form an electrical connection between the charge accumulator 104 and electrical load 106 when closed. The switch 108 is also connected across the terminal of the acceleration sensing element 102. The purpose of the charge accumulator 104 is to

accumulate at least a portion of the electrical energy generated by the acceleration sensing element 102 over a period of time. The other purpose of the accumulator 104 is to discharge the accumulated electrical energy, via the switch 108, into the electrical load 106, at an appropriate time (i.e. upon triggering or switching-ON of the switch). The load is thereby powered to generate an output signal perceivable by an operator.

The charge accumulator 104 may comprise a charge-storage capacitor. The charge-storage capacitor accumulates electrical energy in the form of electric current generated by the acceleration sensing element 102. Where the charge-storage capacitor is connected across the terminals of the acceleration sensing element 102, charge continually builds up in the charge-storage capacitor until the switch 108 is closed for discharging into the electrical load 106.

Electrical energy, or charge, accumulated in the charge-storage capacitor (or other element(s) constituting the charge accumulator 104) is used to power the load 106. Thus the charge-storage capacitor should possess low-leakage current characteristics. This ensures that charge accumulated in the charge-storage capacitor is retained for a sufficiently long duration to enable it to build up, as desired, and be discharged across the load 106.

Low-leakage charge accumulators may include highly insulative ceramics and polymer film capacitors. The polymer film may comprise polypropylene (PP), polyester (PET), polyphenylene sulphide (PPS) or polyethylene naphthalate (PEN).

The charge accumulator 104 may also comprise multiple circuit elements. For example, the charge accumulator 104 may comprise a plurality of capacitors connected together in various configurations to achieve charge storage. Where two, or more, such capacitors are connected in parallel the charge storage provided by those capacitors is additive, thus constituting a larger charge-storage capacity than that provided by either one of the capacitors separately from the other.

The electrical load 106 serves:

- to dissipate the electrical output of the acceleration sensing element 102 as accumulated in the charge accumulator 104, and
- to generate a perceivable signal indicating at least one aspect of the vibration experienced by the acceleration sensing element 102, such as the magnitude, amplitude, frequency or periodicity of the vibration.

The electrical load 106 is powered at least by the portion of the electrical energy that has been stored by the charge accumulator 104, and may also draw a very small current from the acceleration sensing element 102 as the charge accumulator 104 discharges across the electrical load 106. Generally, the current from the acceleration sensing element 102 will not make a significant contribution to the overall power dissipated by the electrical load 106.

The electrical load provides an observable or perceivable indication of vibration, for example using an audial or visual signal. The indication is provided when the electrical load 106 is powered up by the stored charge in the charge accumulator 104, upon triggering of the switch 108.

The indication itself may be adapted to provide information about the vibration. . For example, the time interval between successive switching cycles is indicative of the rate at which the charge accumulator 104 is being charged, and is also inversely correlated with the electrical output of the acceleration sensing element 102. As vibration amplitude, acceleration magnitude or frequency increases, the electrical output of the acceleration sensing element 102 also increases so that the time taken to charge the charge accumulator 104 decreases and thus the time interval between successive triggerings of the switch 108 and activations of the electrical load 106 is reduced. Thus the time interval between successive signals generated upon the activations of the load 106 can indicate certain characteristics or metrics of the vibration experienced by the sensing element 102 or device 100.

The electrical load 106 should be a low-power device so that the charge accumulator 104 can build up sufficient charge to power the electrical load 106 within a practical, typically short, period of time.

- 5 The electrical load 106 should also be a device through which the accumulated charge can be rapidly discharged. Where the charge accumulator 104 includes a charge-storage capacitor, this rapid discharge will enable the voltage across the charge-storage capacitor to be largely reset to its low baseline level for every triggering of the switch 108. This minimizes memory effects (e.g. permanent
10 resistance to complete charging and discharging) resulting from charge retention in the capacitor.

The electrical load may be a light-emitting diode (LED) 202 – see FIG. 2. The LED may provide a visible flash, such as a pulsed flash light, when powered up by the
15 accumulator 104 at every switch-triggering event. The time interval between or frequency of the flashes, may indicate the magnitude of the electrical energy generated by the acceleration sensing element 102, and thus the acceleration or vibration experienced by the device 100 as a whole.

- 20 The electrical load may alternatively be a buzzer 302 – see FIG. 3. The buzzer may provide an audial buzzing or beeping sound when powered up by the charge accumulator 104 at every switch-triggering event. The time interval between or frequency of the beeps may indicate the magnitude of the electrical energy generated by the acceleration sensing element 102 and thus the acceleration or
25 vibration experienced by the device 100 as a whole.

Circuits 200 and 300 of FIGs. 2 and 3 also include a rectifier that will be discussed with reference to FIGs. 8 to 12.

- 30 The electrical load 106 may similarly be any other device that produces an audial, visual or otherwise observable indication of vibration to an operator. For example, the electrical load 106 may be a liquid crystal display (LCD), an electrochromic

display or modulated optical retroreflector, the latter two being non-emissive low-power optical devices.

Using an electrochromic display is useful since such displays use electrochemical
5 redox reactions to affect the colour of electrochromic materials. Thus a colour change can be caused by an applied charge (e.g. that stored in the accumulator 104), that will persist since energy is only required when changing colour and is not required to maintain the change in colour. Thus an electrochromic display can be made to toggle between bistable states each time a switch-triggering event occurs.

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Using a modulated optical retroreflector is also advantageous since such displays use electrically tunable reflective surfaces to control the amount of reflected light. The modulated optical retroreflector can therefore be used to control the flashing of reflected light with each switch-triggering event.

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The ability to power an electrical load providing an observable signal is largely due to the rapid, discrete switch event triggering afforded by switch 108, when coupled with very low current leakage through the load when the switch is OFF. With reference to the device 400 shown in FIG. 4, the switch 402 comprises a switching
20 element, preferably one having a non-linear switching characteristic, presently embodied by an N-type Metal-Oxide Semiconductor Field Effect Transistor (N-MOSFET) 404. The switch 402 comprising the N-MOSFET switches between an OFF, or first, condition in which it substantially prevents current from passing through the electrical load 406, and an ON, or second, condition in which the portion of the
25 electrical energy accumulated in the charge accumulator, presently embodied by charge-storage capacitor 408, is discharged from the charge accumulator across the electrical load 406. The switch 402 further includes a voltage divider circuit comprising C_1 410 and C_2 414. These capacitors 410, 414 determine the switch triggering voltage across the charge accumulator. The voltage divider circuit may
30 also be designed using components other than capacitors, such as resistors.

The transistor-based switch 402 triggers automatically when the capacitor 408 is charged by the acceleration sensing element 412 up to a voltage corresponding to the switch triggering level V_T when the transistor gate reaches the turn-on threshold level. When the switch turns ON, the capacitor 408 is connected to the electrical load 406, enabling the charge stored in the capacitor 408 to discharge across the electrical load 406.

After discharging, the potential difference across the capacitor 408 is reset to its low baseline level thereby resetting the gate voltage to a low level and consequently turning off the transistor. The capacitor 408 can then accumulate charge for the next load activation event, without substantial current leakage.

The accelerometer therefore operates cyclically, with the following cycle:

- conversion – mechanical vibrations are converted into electrical energy by the acceleration sensing element 412;
- accumulation – the capacitor 408 accumulates electrical energy generated from the acceleration sensing element 412;
- transfer – the accumulated electrical energy is transferred to (or discharged into) the electrical load 406 via the switch 402 upon triggering.
- dissipation – the electrical energy dissipates across the electrical load generating perceivable indicative signals representative of the sensing information.

As the charge storage capacitor 408 charges up during charge accumulation, it pulls up the gate voltage of the transistor 404 via the voltage divider comprising 410 and 414. Once the gate voltage (i.e. the switch/gate trigger voltage) of the transistor 404 reaches the intrinsic turn-on threshold V_{GT} , the transistor will be switched on, thereby enabling the charge from the charge-storage capacitor 408 to dissipate across the load 406. Thus the transistor 404 is activated once the potential difference across the charge accumulator 408 satisfies the following equation:

$$V_{GT} = V_T \frac{C_1}{C_1 + C_2}$$

where:

- V_T is the switch triggering voltage across the charge accumulator 408;
- V_{GT} is the gate transition voltage, or the threshold voltage at which the transistor gate intrinsically turns on;
- C_1 is the capacitance of capacitor 410; and
- C_2 is the capacitance of capacitor 414.

Where the capacitance of capacitors 410, 414 is the same, the voltage drop across them will be the same. Thus V_T will be twice V_{GT} . Similarly, $V_T - V_{GT}$ will be the voltage drop across capacitor 410 when the gate of the transistor 404 is activated, and V_T will be the voltage drop across the load 406.

The preferred use of capacitors, rather than resistors, in the voltage divider circuit to bias the gate terminal of the transistor significantly reduces current leakage. This allows for more effective charge accumulation and retention in capacitor 408, when compared with resistor-based circuits.

In the circuit of FIG. 4, as the potential difference across the gate of the transistor 404 approaches V_{GT} , a passage for leakage current into the electrical load can be created through the transistor 404. As the capacitor 408 gradually charges from the small current emitted by the acceleration sensing element 412, the gate voltage at the transistor 404 gradually rises but stays, until triggering, at a sub-threshold level (i.e. below the triggering voltage V_{GT}). At the sub-threshold level, the transistor 404 is partially turned on and induces a small but substantial current leakage at the transistor's drain. This enables a current to leak through the electrical load 406. For loads 406 with low internal resistance the current leakage may be a substantial portion of that which is generated by the acceleration sensing element 412. This would prevent or severely hinder the continued accumulation of sufficient electrical charge in the charge accumulator 408 to properly switch on the electrical load 406.

It is therefore preferred that the switch turns ON in an abrupt manner once the voltage across capacitor 408 reaches the triggering level – the level at which the gate of the transistor reaches V_{GT} . FIG. 5 shows a circuit 500 incorporating the same circuit elements as circuit 400, except that the switch 502 comprises a plurality of non-linear switching elements. While various non-linear switching elements and arrangements including such elements may be used, the present embodiment employs two transistors 504, 506. The non-linear switching elements are arranged in a cascading structure, presently a cascading pair – the activation (i.e. switching to the on-state) of a first one of the plurality of non-linear switching elements is required to enable activation of the next non-linear switching element in the cascading arrangement and, where three or more non-linear switching elements are used, activation of the next non-linear switching element enables activation of the third non-linear switching element in the cascade, and so on.

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The cascading pair shown in FIG. 5 comprises an N-MOSFET 504 and a P-type MOSFET (P-MOSFET) 506 that is downstream of the N-MOSFET – in other words, the N-MOSFET 504 must be activated in order to activate the P-MOSFET 506. In this arrangement, the gate of the first transistor 504 is connected to the charge-storage capacitor 508 through the voltage divider capacitors 510, 512 as per FIG. 4. In addition, the drain of the first transistor 504 is connected to the gate of the second transistor 506. The drain of the first transistor, or the gate of the second transistor is also connected to the charge accumulator 508 via a pull up resistor 516. The pull-up resistor is preferably one of a high ohmic value, such as in the range of Giga-ohms, to minimize leakage current through the first transistor 504.

When the built-up voltage in the charge accumulator 508 is below the switch triggering level, the first transistor 504 inhibits current flow through the pull up resistor 516, such that the voltage drop across the pull up resistor 516 (and also across the source to gate of the second transistor) is very low to turn off the second transistor 506. As a consequence, the leakage current into the load 518 is very low,

allowing the charge generated by the sensing element to be retained and accumulated in the charge accumulator 508.

As the built-up voltage in the charge accumulator 508 approaches near to the switch
5 triggering level, the current flowing through the pull up resistor 516 increases exponentially to turn on the second transistor 506. Such a cascading arrangement of two non-linear switching elements produces vastly improved switching behaviour so that the second transistor (P-MOSFET) connected at its drain to the electrical load
518 can be abruptly turned on when the voltage across the charge-storage capacitor
10 508 reaches the triggering level.

In addition, to keep the transistor 506 open for an extended period after being switched on, a capacitor may be connected across the gate of the transistor 506, such that it is also in parallel with the pull-up resistor 516. Such an arrangement is
15 shown in the circuit 600 of FIG. 6. Capacitor 602 is connected across the gate of the transistor 606 in parallel with the pull-up resistor 604, and serves to maintain the gate voltage of the second transistor 606 for a short duration after triggering of switch 608. The effect of the capacitor 602 is that the second transistor 606 in the cascading pair of transistors 606, 610 exhibits an hysteresis behaviour, allowing the
20 transistor 606 to remain in the on-state (i.e. the state in which current is intended to flow through from source to drain) for an extended period to facilitate more complete discharge of the charge-storage capacitor 612 into the electrical load 614.

Yet further sharpness of the switching operation can be achieved using additional
25 non-linear switching elements to form a cascading connection. The cascading connection may be a multi-stage cascading connection. The circuit 700 in FIG. 7 includes six cascading transistors with alternating n- and p-type, 704, 706, 708, 710, 716, 718. The transistors 708, 710 are activated in the same manner as the transistor pair 610, 606 described in relation to FIG. 6, but instead of connecting the load 712
30 to the charge-storage capacitor 714 upon switching on transistor 710, the on-state of transistor 710 creates the potential difference across the gate of transistor 716 needed to activate transistor 716 and so on. Every transistor in the cascade must

activate in-turn before the last transistor 718 switches on, thereby connecting the charge-storage capacitor 714 to the electrical load 712.

The gate of each transistor is accompanied by an impedance – e.g. impedance 711 at the gate of transistor 710. For the N-MOSFETs the impedance may include a pull down resistor and for the P-MOSFETs the impedance may include a pull up resistor. Alternatively, each impedance may comprise a capacitor, or a capacitor and resistor.

Where an impedance comprises a capacitor and resistor, the two components may be in parallel so as to induce hysteresis-type behaviour as discussed with reference to FIG. 6. This is particularly important for transistor 718, because transistor 718 should remain switched on until the charge accumulator 714 is substantially depleted of charge. This minimizes memory effects caused by incomplete discharge cycles.

Vibrations are typically alternating or periodic in nature. They are sometimes of a particular frequency, and their amplitude can change over time. For this reason, the current generated by the acceleration sensing element (e.g. device 102 of FIG. 1) is usually an AC. To avoid charging and then discharging the capacitors by the acceleration sensing element of each circuit, the AC should be rectified.

A rectifier is consequently present in each of the circuits shown in FIGs. 4 to 7 – labelled 450, 550, 650 and 750 in respective ones of FIGs. 4 to 7. FIGs. 8, 10 and 12 provide examples of rectifier circuits that can be incorporated into circuits 400, 500, 600 and 700.

In the circuit 800 of FIG. 8 a half-wave rectifier in the form of a diode 802 is connected to one terminal 804 of the acceleration sensing element 806. The other circuit elements are the same as those shown in FIG. 1.

The diode 802 permits current to flow in the direction of arrow X, but not in the opposite direction. The resulting effect on an AC is shown in FIG. 9 – the original

wave 900 is shown in broken lines and the rectified wave 902 is shown in solid lines. The sinusoidal portion of wave 902 coincides with wave 900.

A full-wave rectifier is shown in FIG. 10. In this embodiment, current that leaves the acceleration sensing element 1000 in the direction of arrow X passes through diode 1002 and into the circuit 1004. Similarly, current that leaves the sensing device 1000 in the direction of arrow Y passes through diode 1006 and is thus forced to pass through the circuit in the same direction as current following arrow X. Diodes 1008, 1010 simply permit the current to return to the opposite terminal of the sensing device 1000 to that from which it was transferred by the sensing device 1000. FIG. 11 shows the fully-rectified waveform with the original wave 1100 shown in broken lines and the fully-rectified wave 1102 shown in solid lines.

Other rectifier arrangements may be used depending on the nature of the load and the characteristics of the sensing device. For example, FIG. 12 shows a full-wave rectifier voltage-doubler arrangement. Since capacitor 1200 is, in effect, connected across the terminals of the sensing device 1202, the potential difference across the capacitor 1200 is the same (when fully charged) as the potential difference across the sensing device 1202. By placing another capacitor 1204 in series with capacitor 1200, the voltage drop across the load 1206 is doubled in cases where the capacitors 1200, 1204 have the same capacitance.

EXAMPLES

A prototype battery-less (self-powered) accelerometer circuit was built in accordance with the schematic circuit 1300 shown in FIG. 13, using an LED 1302 as the electrical load. The acceleration sensing element 1304 was configured to sense acceleration and was implemented using a piezoelectric cantilever beam with a fixed end attached to a vibration surface of a mechanical shake. A proof mass was attached to the free end of the cantilever beam. The acceleration-sensing element 1304 was connected in parallel to the charge-storage capacitor 1306 in the form of a low-leakage 220nF polyester capacitor via a half-wave rectifier in the form of a single diode 1308. The switch or switching circuit 1310 was implemented using cascading

pairs of MOSFETs 1312, 1314, 1316, each pair comprising an N-MOSFET and a P-MOSFET, similar to the embodiment shown in FIG. 5. The impedance 1318 attached to the drain of each transistor in each pair of transistors 1312, 1314, 1316 comprised a capacitor and resistor in parallel. The circuit was designed to achieve switching of the switch when the built-up voltage across the charge-storage capacitor 1306 reached 2.6V.

The switching profile of the switching circuit 1310 over the LED load 1302 was first investigated by charging up the charge-storage capacitor 1306 using a fixed direct current of 1 nA from a source-meter instead of the acceleration-sensing element 1304. The voltage across the LED load 1302 was monitored to capture the switching moment when the charge-storage capacitor 1306 approached the switching threshold level of approximately 2.6 V. The captured switching profile of the end transistor 1320, as exhibited in FIG. 14, indicated that the switch circuit was fully turned on to activate the LED (which was observed to have flashed). It is to be noted that within the rise-time of 200 μ s, the capacitor voltage was expected to have increased by only approximately 0.9 μ V to trigger a full switching at the end transistor 1320 beyond its sub-threshold operating region. The results thus demonstrated an ultra-sharp switching at the end transistor 1320 that is highly responsive to the voltage change at the charge-storage capacitor 1306 at the switch triggering level. Such abrupt switching was enabled by the cascading non-linear switching transistors (i.e. pairs 1312, 1314, 1316) being arranged in multiple stages, and minimization of current leakages through the electrical load 1302.

The acceleration-sensing element 1304 with its fixed end mounted on the mechanical shaker was then incorporated into the platform, instead of the source-meter, to charge up the charge-storage capacitor 1306. The voltage across the charge-storage capacitor 1306 was monitored to observe the charging up action by the acceleration-sensing element 1304 and the discharging action triggered by the switch mechanism 1310, as shown in FIG. 15. Under a vibration frequency of 45 Hz and acceleration of 1 g, it was observed that the capacitor 1306 was charged up gradually by the current output from the acceleration-sensing element 1304.

As the voltage approached the switch triggering level of 2.6 V, the voltage across the capacitor 1306 returned rapidly to the low baseline value under the discharging action of the switch 1310. The charging and discharging action was also repetitive and produced a consistent time interval, T , between individual discharging cycles under the same vibration frequency and acceleration. The discharge interval, T , was observed to decrease along with the acceleration magnitude in a fairly inverse-linear relationship, as illustrated in the plot of $1/T$ vs Acceleration in FIG. 16.

Corresponding to every discharge action, the LED 1302 produced a momentarily observable flash. The frequency of the flash may be taken as an indicative signal to alert the operator of the intensity of the vibration, so that the higher the frequency of the flash observed, the larger the vibration measured. Alternatively, by calibrating the flash frequency against the vibration/acceleration, a more precise accelerometer may be achieved whereby the frequency of the flash serves as a direct measurement of the vibration acceleration.

In another experiment as illustrated in FIG. 17, the electrical load 1302 was replaced by a low-power piezoelectric buzzer module 1700 with an operating voltage of 1.8 V. The buzzer module 1700 was configured to produce an audible beep when powered up by the charge-storage capacitor 1702 upon every triggering of switch 1704. The charge-storage capacitor 1702 was increased to 4.7 μF to provide a sufficiently large electrical energy to drive the buzzer module. The voltage across the charge-storage capacitor 1702 was again monitored to observe the charging and discharging profile of the acceleration-sensing element 1708 and the switch 1704.

An example of the charging and discharging profile across the charge-storage capacitor 1702 is shown in FIG. 18, under a vibration frequency of 45 Hz and acceleration of 3 g. As the voltage approached 2.6 V, the charge-storage capacitor 1702 was rapidly discharged through the buzzer module 1700 which correspondingly produced an audible beep. The charging and discharging action was again repetitive with a consistent time interval, T , under the same vibration condition. The discharge

interval, T , was observed to decrease along with the acceleration in an approximately inverse-linear relationship, as illustrated in the plot of $1/T$ vs Acceleration in FIG. 19.

- 5 This demonstrates that a very small current generated by the acceleration sensing element can be accumulated and used to drive a high-leakage electrical load. In particular, that current may be used to drive a load to display the acceleration or vibration sensing signal directly observable by people, in a completely self-powered circuit driven solely by the acceleration sensing element without any assistance from
- 10 an external power source. This function is facilitated by the use of high impedance sensing element, such as a piezoelectric sensing element made of dielectric material, low leakage charger accumulator, and rapid, sharp triggering operation of the switch when connecting the load to the charge accumulator.
- 15 While exemplary embodiments have been presented in the foregoing detailed description of the invention, it should be appreciated that a vast number of variations exist. It should further be appreciated that the exemplary embodiments are only examples, and are not intended to limit the scope, applicability, operation, or configuration of the invention in any way. Rather, the foregoing detailed
- 20 description will provide those skilled in the art with a convenient road map for implementing an exemplary embodiment of the invention, it being understood that various changes may be made in the function and arrangement of steps and method of operation described in the exemplary embodiment without departing from the scope of the invention as set forth in the appended claims.

CLAIMS

1. A self-powered acceleration sensing device comprising:
 - an acceleration sensing element for converting vibration into electrical energy;
 - a charge accumulator electrically connected to the acceleration sensing element to accumulate at least a portion of the electrical energy converted from vibration by the acceleration sensing element over a period of time;
 - a load to be powered by discharge of the portion of the electrical energy from the charge accumulator and being capable of producing an output that is directly observable by an operator; and
 - a switch for controlling discharge of electrical energy from the charge accumulator to the load,whereby the switch performs switching between a first condition in which current is substantially prevented from passing through the load, and a second condition in which the portion of the electrical energy is discharged from the accumulator to the load; and
 - switching is controlled by an amount of energy accumulated in the charge accumulator.
2. A self-powered acceleration sensing device according to claim 1, wherein the output is a visual or audial output.
3. A self-powered acceleration sensing device according to claim 1-2, wherein the charge accumulator is configured to repetitively accumulate and discharge electrical energy and a time interval between successive discharges depends on at least one aspect of the sensed vibration.
4. A self-powered acceleration sensing device according to claim 3, wherein the at least one aspect of the sensed vibration is indicated to an operator based on the time interval between successive visual or audial outputs generated by successive discharges of the electrical energy from the charge accumulator.

5. A self-powered acceleration sensing device according to claims 3-4, wherein the at least one aspect of the sensed vibration comprises the magnitude of the acceleration.

6. A self-powered acceleration sensing device according to claim 5, wherein the time interval of successive discharges or the successive visual or audial outputs is inversely correlated to the acceleration magnitude.

7. A self-powered acceleration sensing device according to any preceding claim, wherein the switch comprises at least one transistor configured to turn on to operate the switch to the second condition when a level of electrical energy accumulated in the charge accumulator reaches a pre-determined threshold level.

8. A self-powered acceleration sensing device according to claim 7, wherein the switch comprises a plurality of transistors configured to turn on to operate the switch to the second condition when the level of charge accumulated in the charge accumulator reaches a pre-determined threshold level.

9. A self-powered acceleration sensing device according to claim 8, wherein the plurality of transistors are arranged in a cascading arrangement and are configured to be activated in-turn thereby operating the switch to the second condition when the level of charge accumulated in the charge accumulator reaches a pre-determined threshold level.

10. A self-powered acceleration sensing device according to any one of claims 7-9, wherein at least one transistor has a gate connected to a capacitor, the respective capacitor for extending a duration of an on-state of the respective transistor and thereby extend a duration of the second condition of the switch.

11. A self-powered acceleration sensing device according to any preceding claim, wherein the switch further includes a voltage divider circuit connecting the charge accumulator to the at least one transistor.

12. A self-powered acceleration sensing device according to claim 11, wherein the voltage divider comprises at least two capacitors.

13. A self-powered acceleration sensing device according to any preceding claim, wherein the acceleration sensing element comprises a dielectric sensing element.

14. A self-powered acceleration sensing device according to claim 13, wherein the dielectric sensing element comprises a piezoelectric material.

15. A self-powered acceleration sensing device, according to claim 14, wherein the dielectric sensing element has a cantilever beam structure.

16. A self-powered acceleration sensing device, according to claim 14, wherein the dielectric sensing element has a diaphragm structure.

17. A self-powered acceleration sensing device according to any preceding claim, wherein the charge accumulator comprises a charge-storage capacitor.

18. A self-powered acceleration sensing device, according to claim 17, wherein the capacitor is a ceramic or polymer film capacitor.

19. A self-powered acceleration sensing device according to any preceding claim, further comprising a rectifier between the acceleration sensing element and the charge accumulator.

20. A self-powered acceleration sensing device according to any preceding claim, wherein the load is a light emitting diode (LED) configured to produce light during discharge of the electrical energy from the charge accumulator.

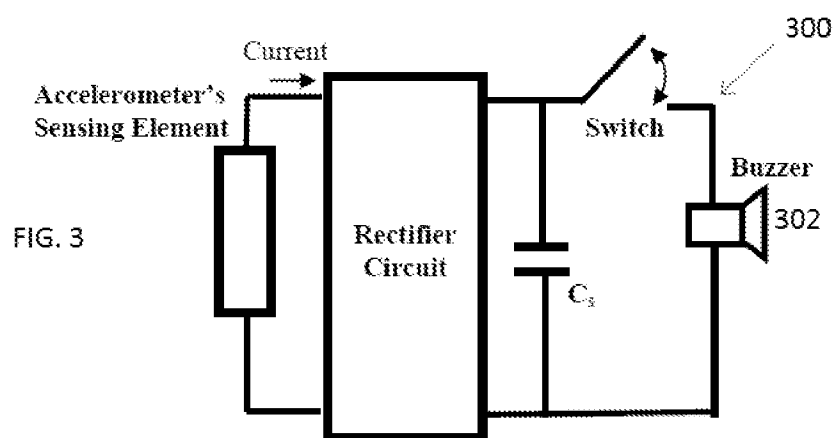
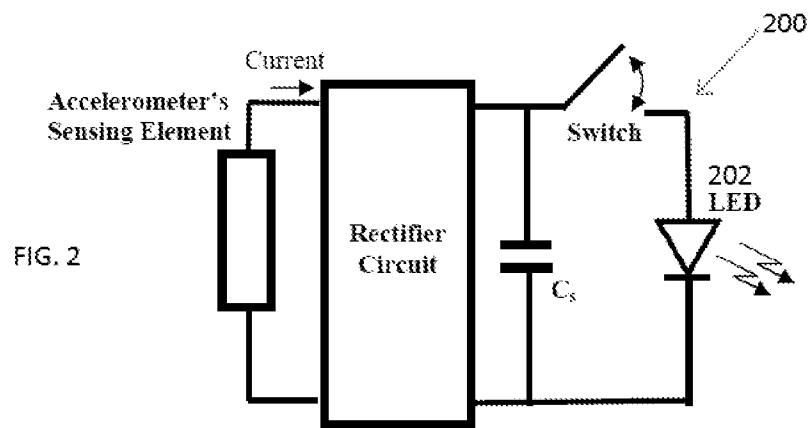
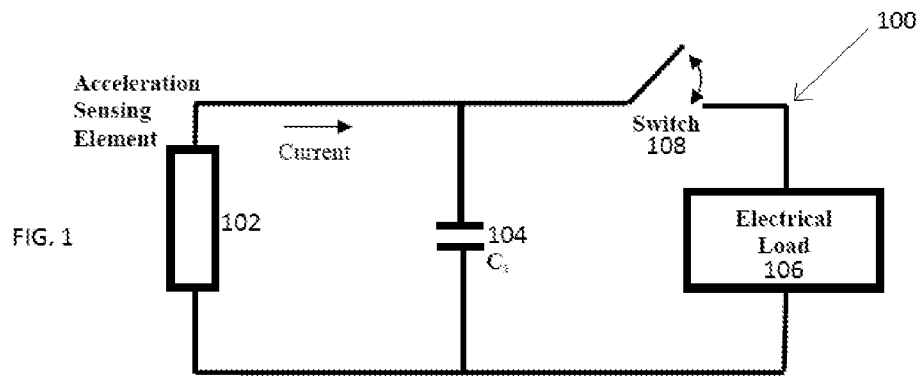
21. A self-powered movement-sensing device according to claim 20, wherein the LED is configured to produce visible pulsed light during discharge of the electrical energy from the charge accumulator.

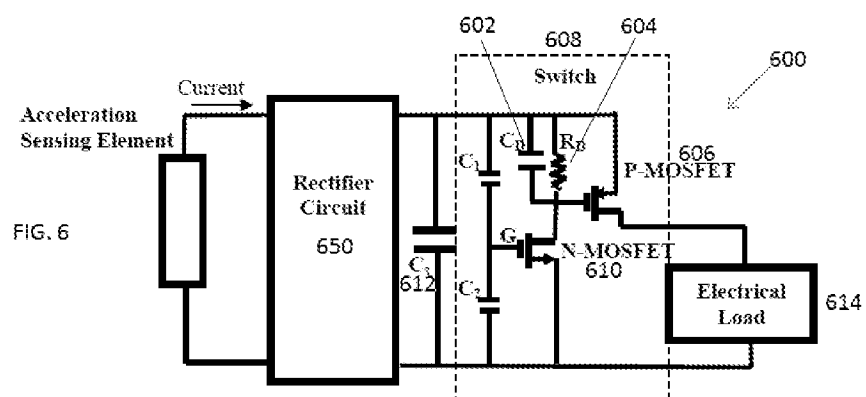
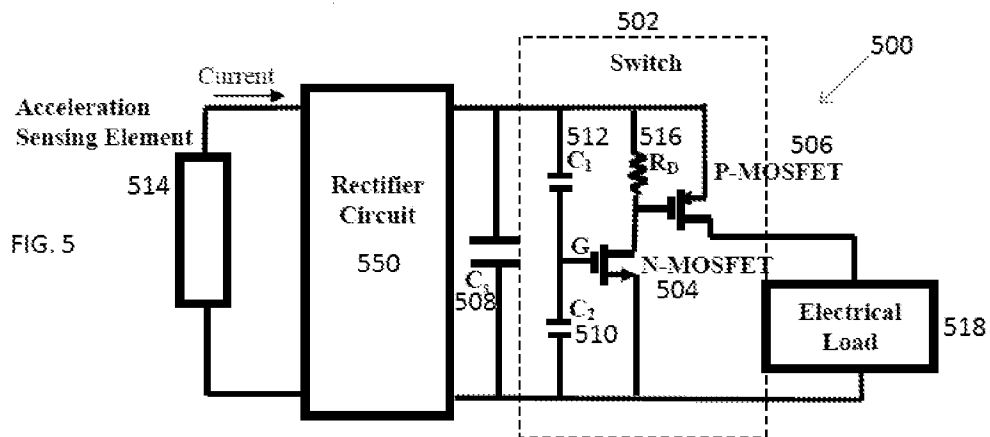
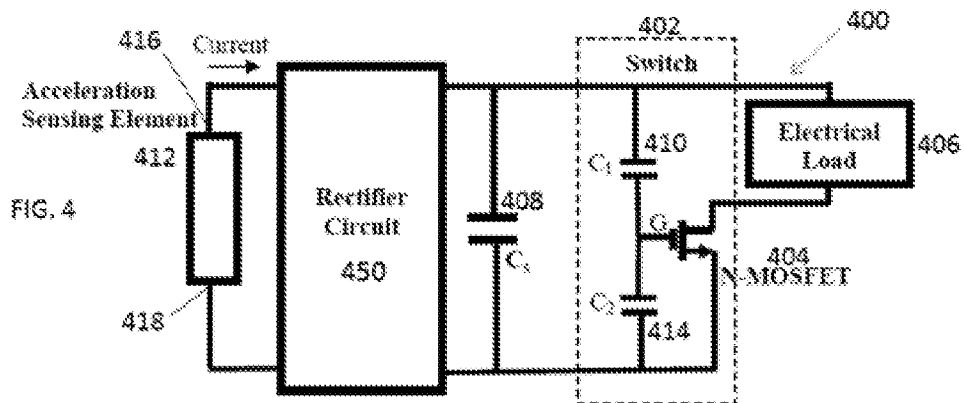
22. A self-powered acceleration sensing device according to any one of claims 1 to 19, wherein the load is a buzzer configured to produce an audible sound during discharge of the electrical energy from the charge accumulator.

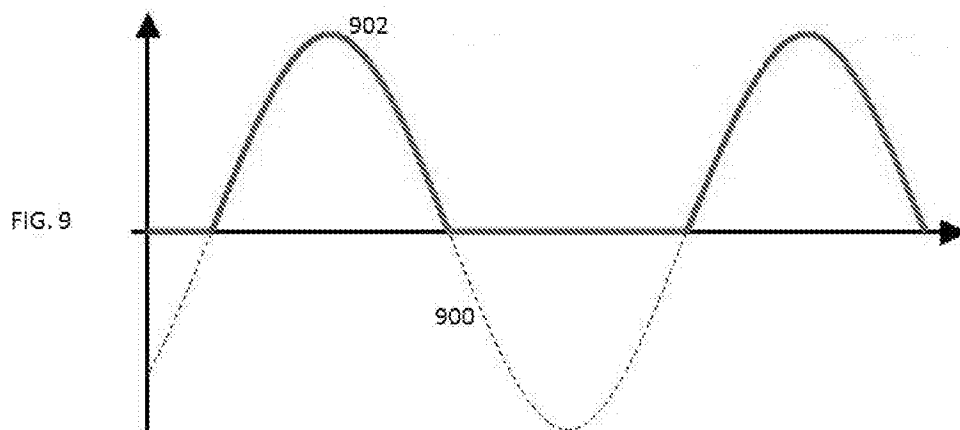
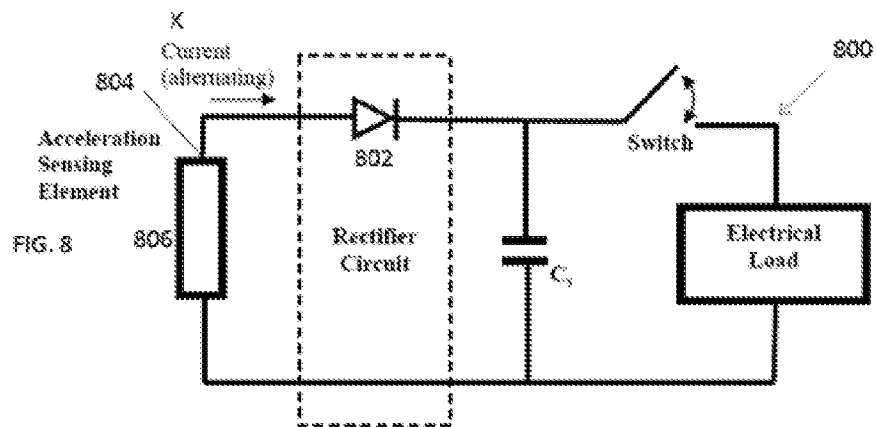
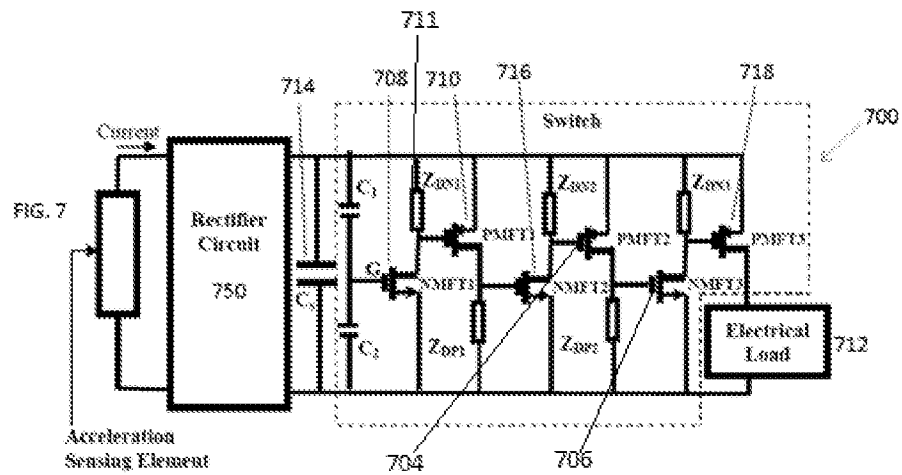
23. A self-powered acceleration sensing device according to any one of claims 1 to 19, wherein the load is a liquid crystal display and the output is displayed on the liquid crystal display.

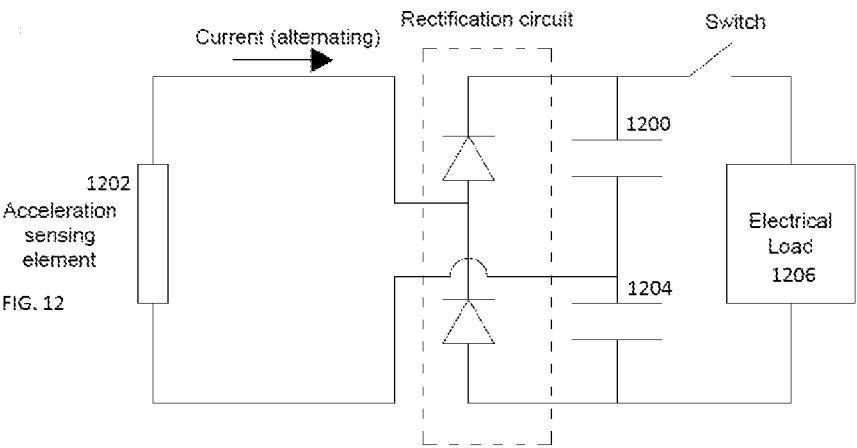
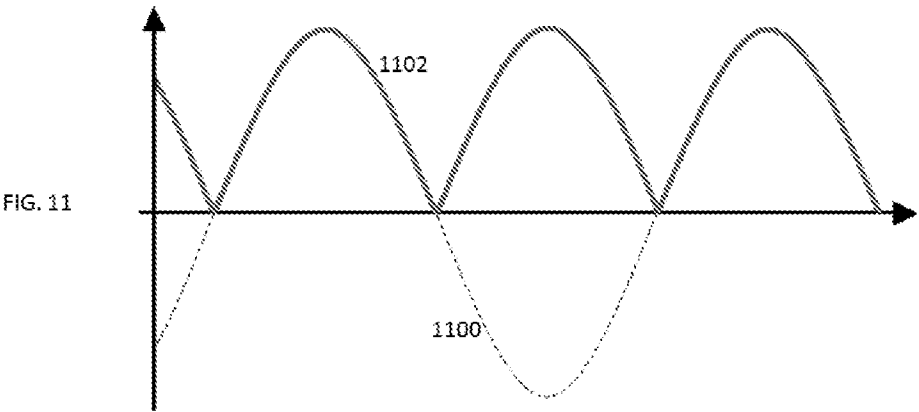
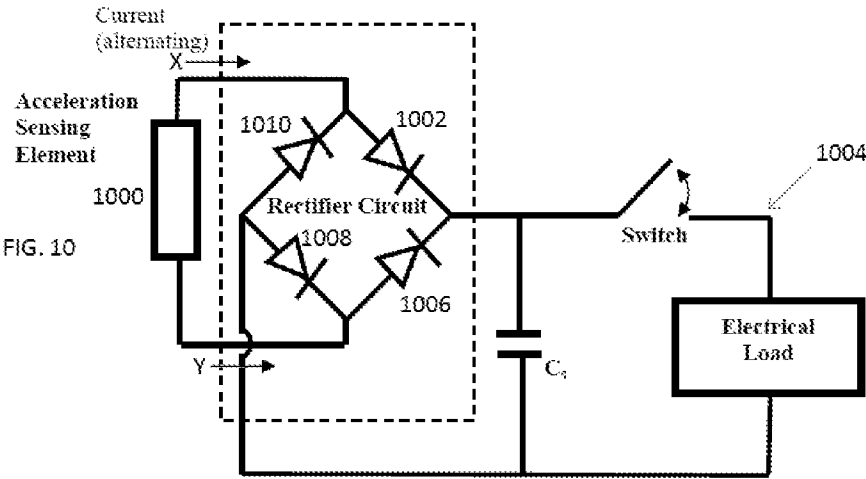
24. A self-powered acceleration sensing device according to any one of claims 1 to 19, wherein the load is an electrochromic display and the output is displayed on the electrochromic display.

25. A self-powered acceleration sensing device according to any one of claims 1 to 19, wherein the load is a modulated optical retroreflector and the output is displayed on a display of the modulated optical retroreflector.









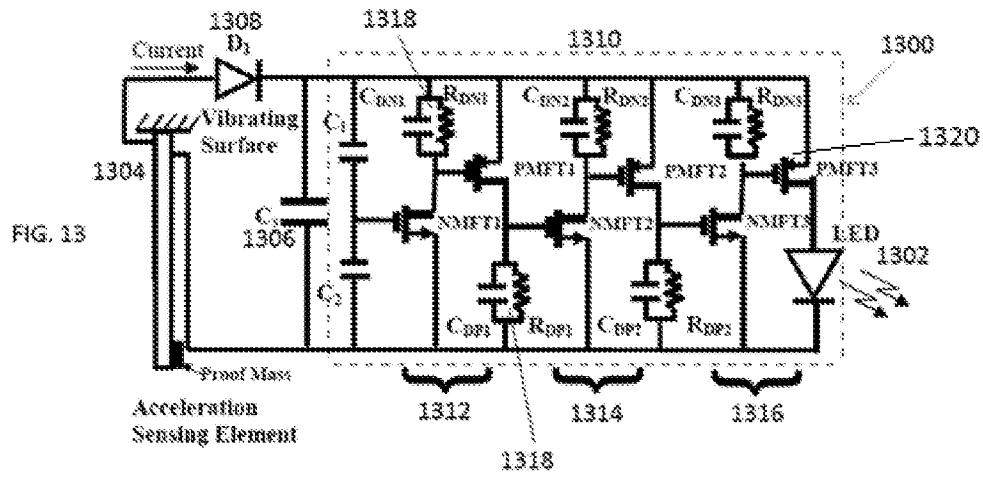


FIG. 14

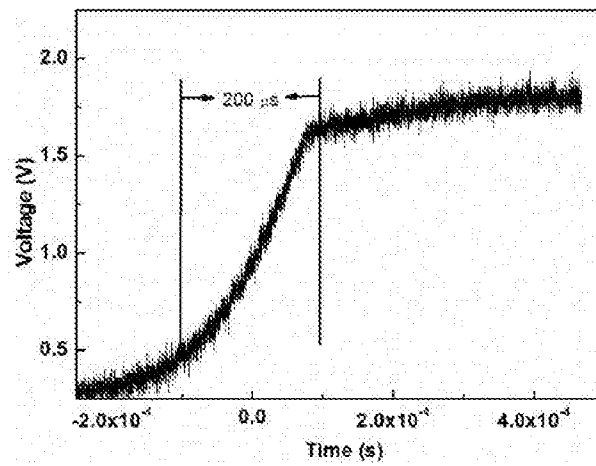


FIG. 15

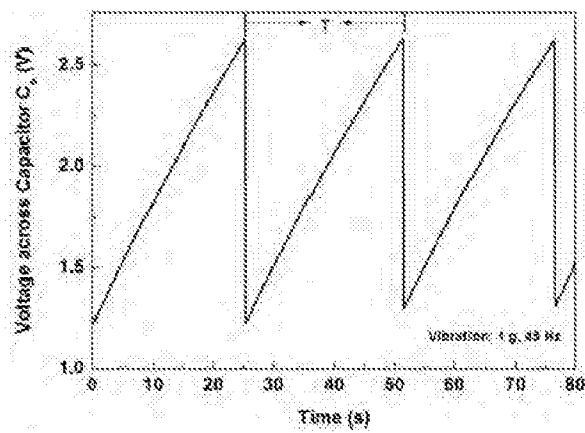


FIG. 16

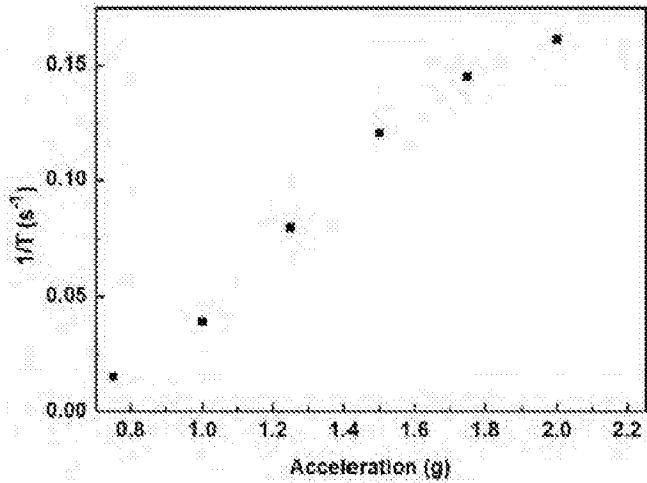


FIG. 17

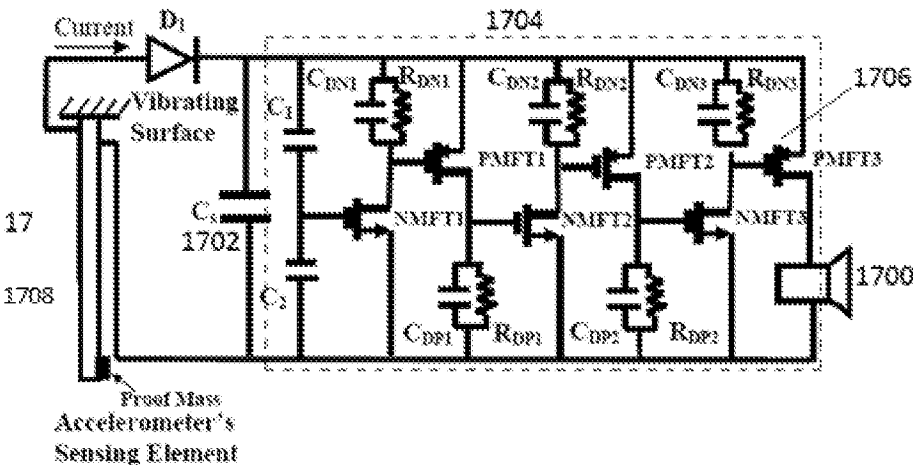


FIG. 18

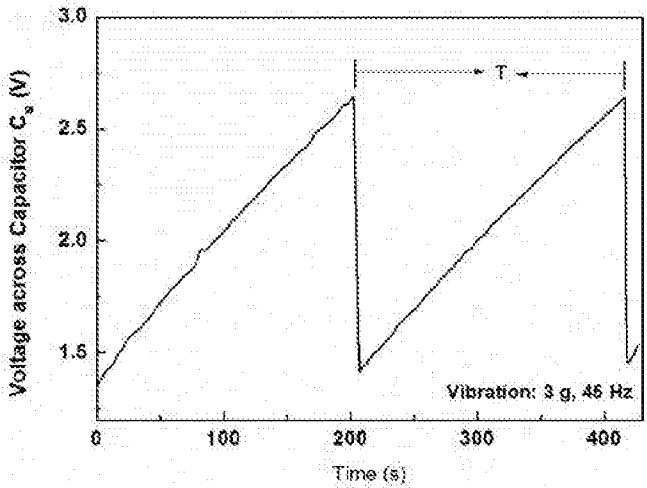
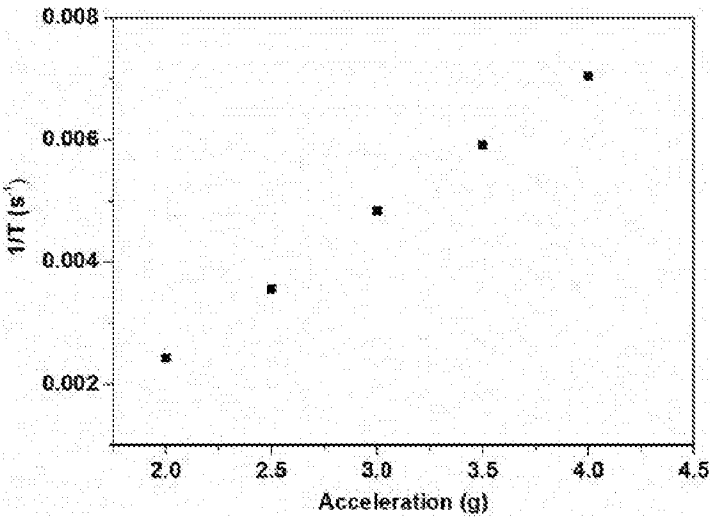


FIG. 19



INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2016/050086

A. CLASSIFICATION OF SUBJECT MATTER

G01H 11/08 (2006.01) H02J 7/00 (2006.01)

According to International Patent Classification (IPC)

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01H

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)

FAMPAT, IEEE: self-powered, battery less, acceleration, vibration, resonate, sense, detect, identify, accumulator, charging, discharging, switch, threshold, load and other related terms

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 2415619 A1 (BRIDGEPORT S.R.L.) 8 February 2012 Figs. 5 and 7; Paras.[0029]-[0030] and [0048]-[0060]	1-25
X	US 2004/0078662 A1 (HAMEL M. J. ET AL.) 22 April 2004 Figs. 3a-5; Paras. [0047]-[0059], [0071] and [0087]	1-25
X	WO 2007/063271 A2 (ROLLS-ROYCE PLC) 7 June 2007 Figs. 1 and 2; Page 2 lines 11-25, Page 6 line 8- page 7 line 19, Page 8 line 22- page 9 line 10 and Page 10 lines 2-5	1-25

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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Date of the actual completion of the international search

31/03/2016

(day/month/year)

Date of mailing of the international search report

07/04/2016

(day/month/year)

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INTERNATIONAL SEARCH REPORT

International application No.

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C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
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A	JING B. Y. ET AL., Demonstration of self-powered accelerometer using piezoelectric micro-power generator. <i>2013 IEEE Student Conference on Research and Development (SCoReD)</i> , 17 December 2013, pages 560-563 [Retrieved on 2016-03-31] (DOI: 10.1109/SCORED.2013.7002654) Whole document	

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Information on patent family members

International application No.

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