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Deterre et al.

(54) **ENERGY HARVESTER DEVICE FOR AUTONOMOUS INTRACORPOREAL CAPSULE**

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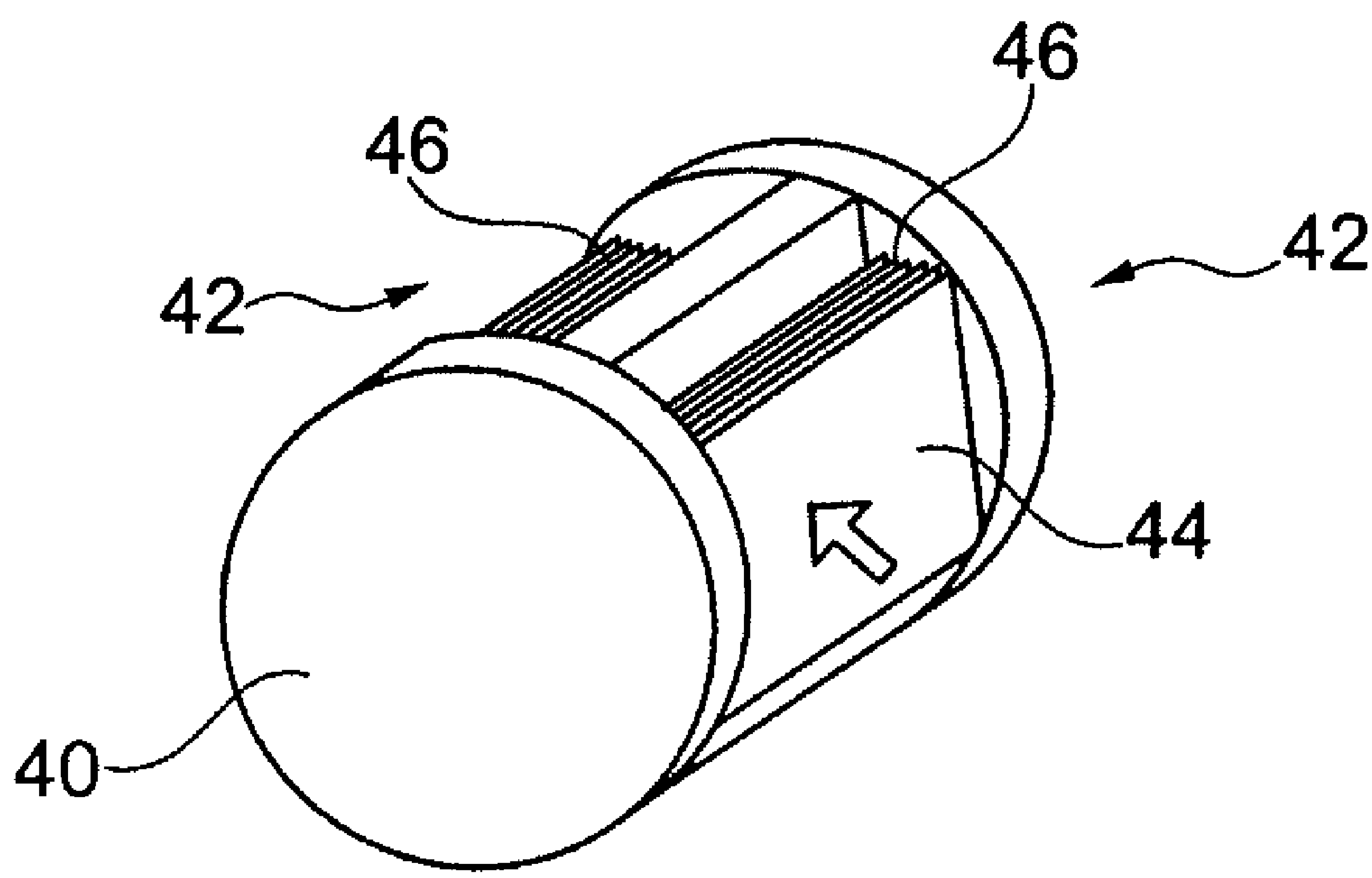
(57) **ABSTRACT**

An energy harvester device for an autonomous intracorporeal leadless capsule comprises a surface formed on the outside of the body of the capsule that is deformable under the effect of pressure variations in the environment surrounding the capsule. A first capacitor electrode coupling to the deformable surface with the interposition of a damping element forming high-pass filter with respect to pressure variations in the surrounding medium, and a second capacitor electrode mounting on a support connected to the body. The movement of the deformable surface produces a modification of surfaces in vis-à-vis of the two electrodes and/or of the dielectric gap which separates them, with a variation of the capacity of said capacitor. The capacitor is preloaded when its capacity is maximum, and unloaded by transferring energy into storage circuit when this capacity decreases from a reduction in surfaces in vis-à-vis and/or of an increase of the dielectric gap.



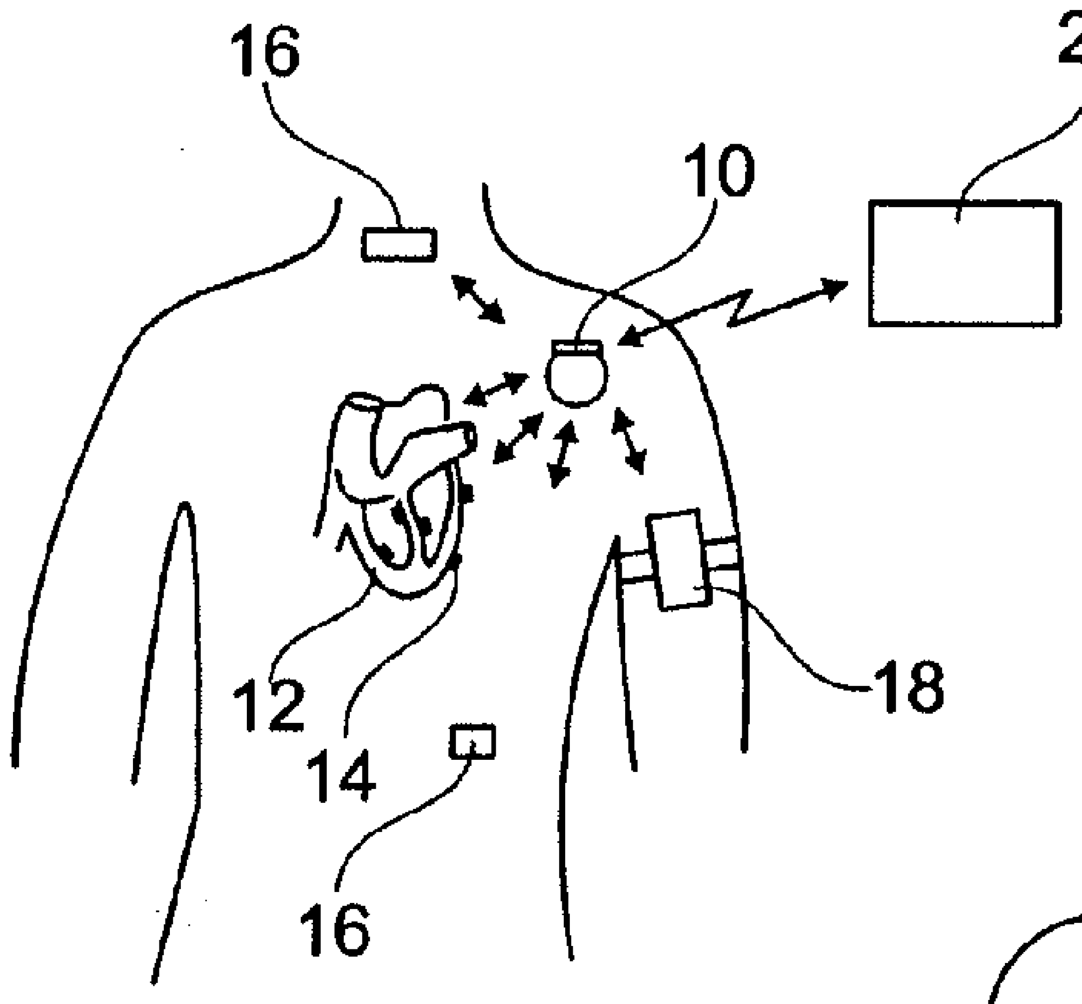


Fig. 1

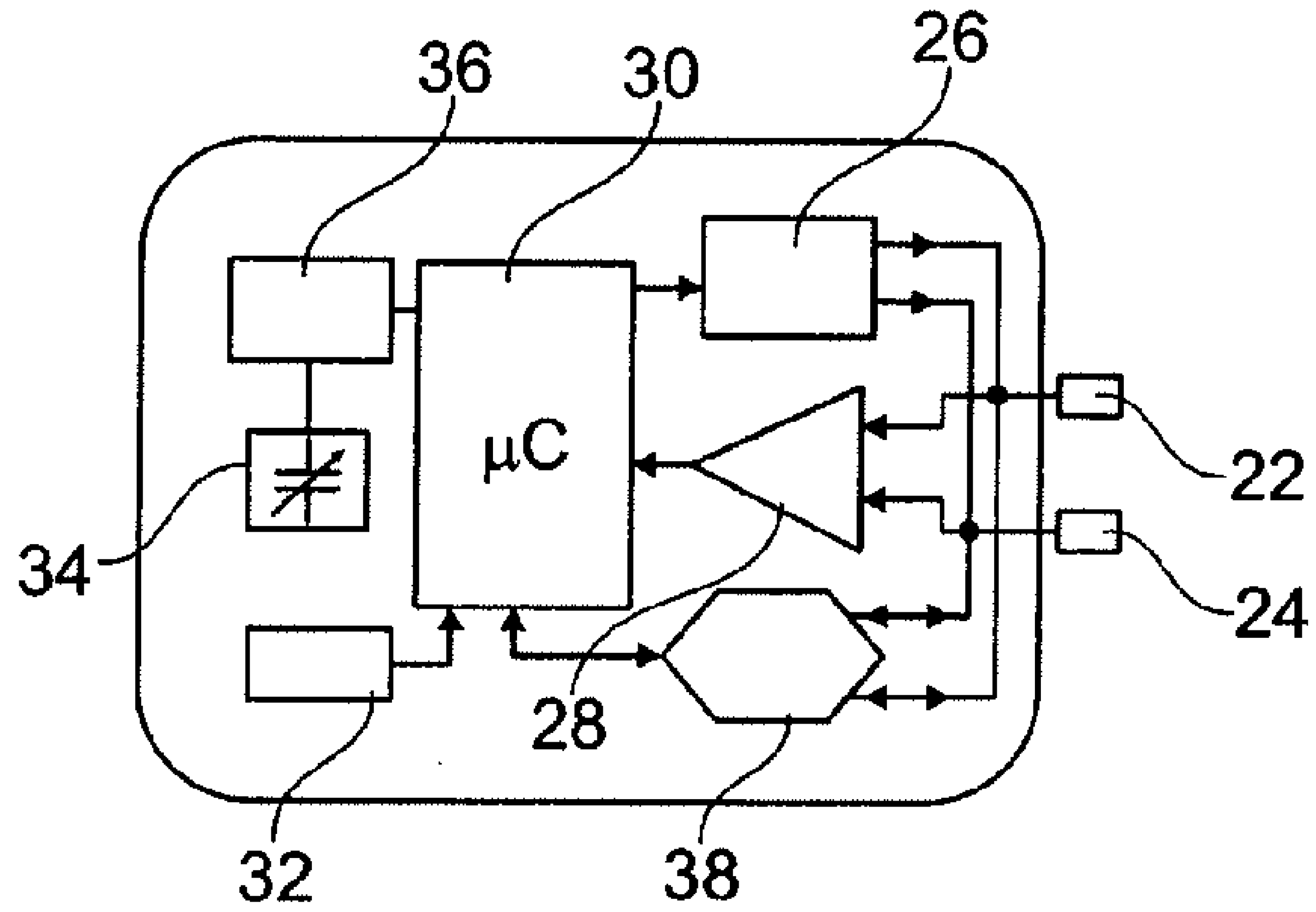


Fig. 2

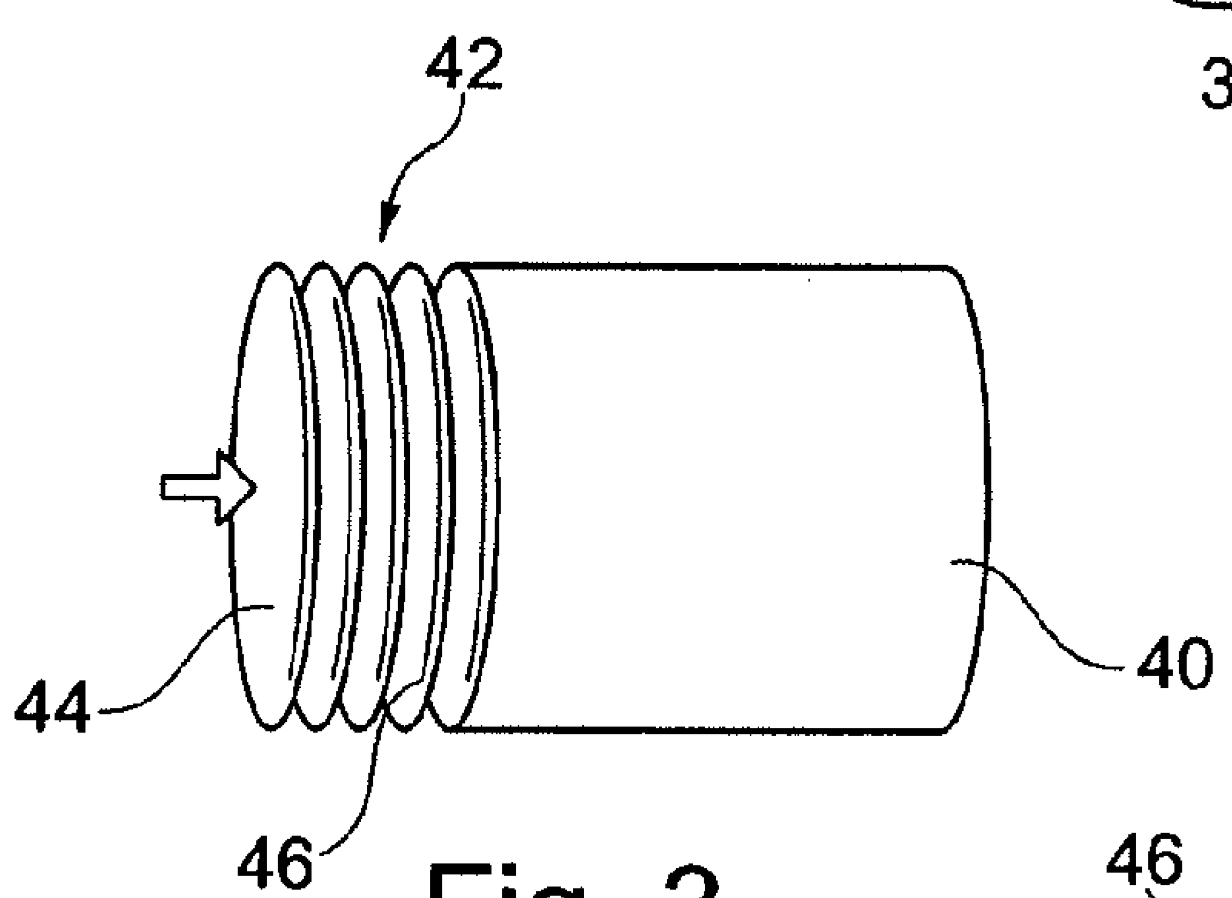


Fig. 3

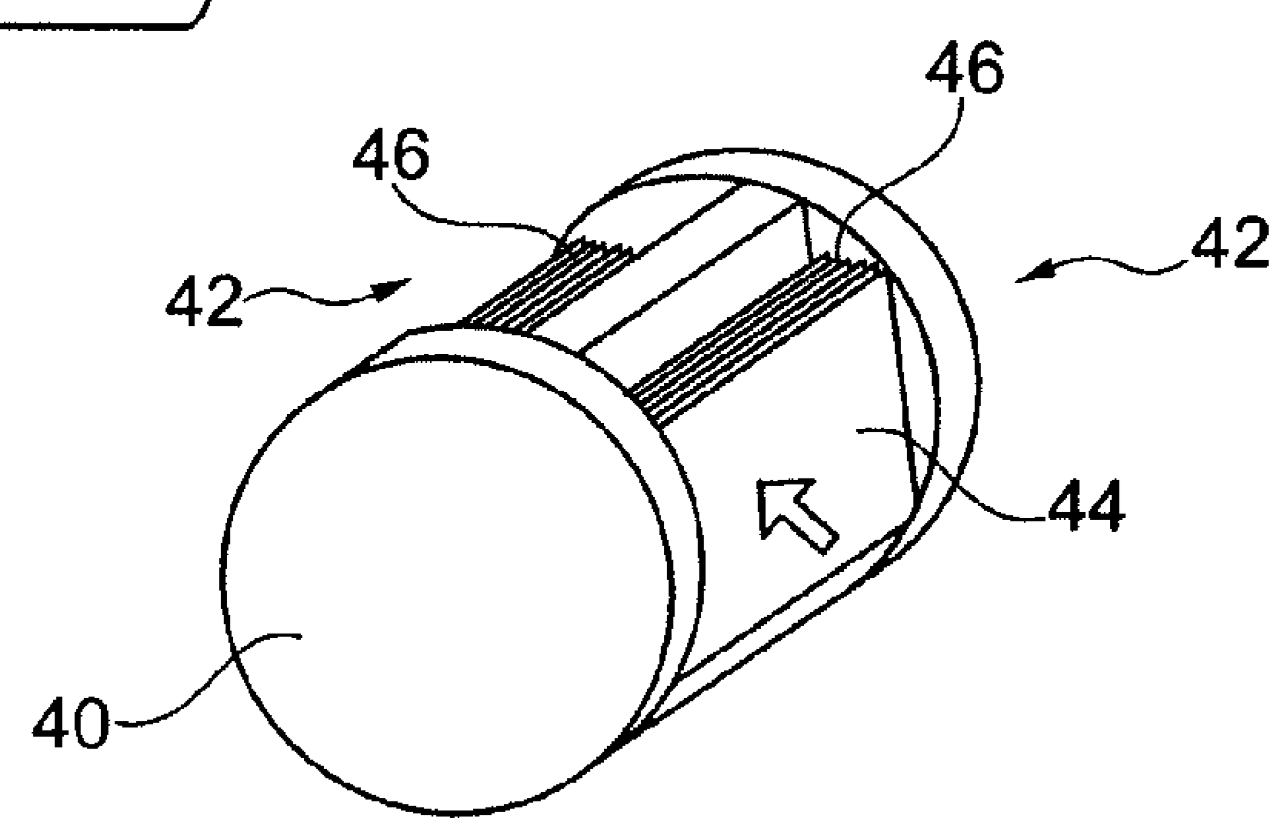


Fig. 4

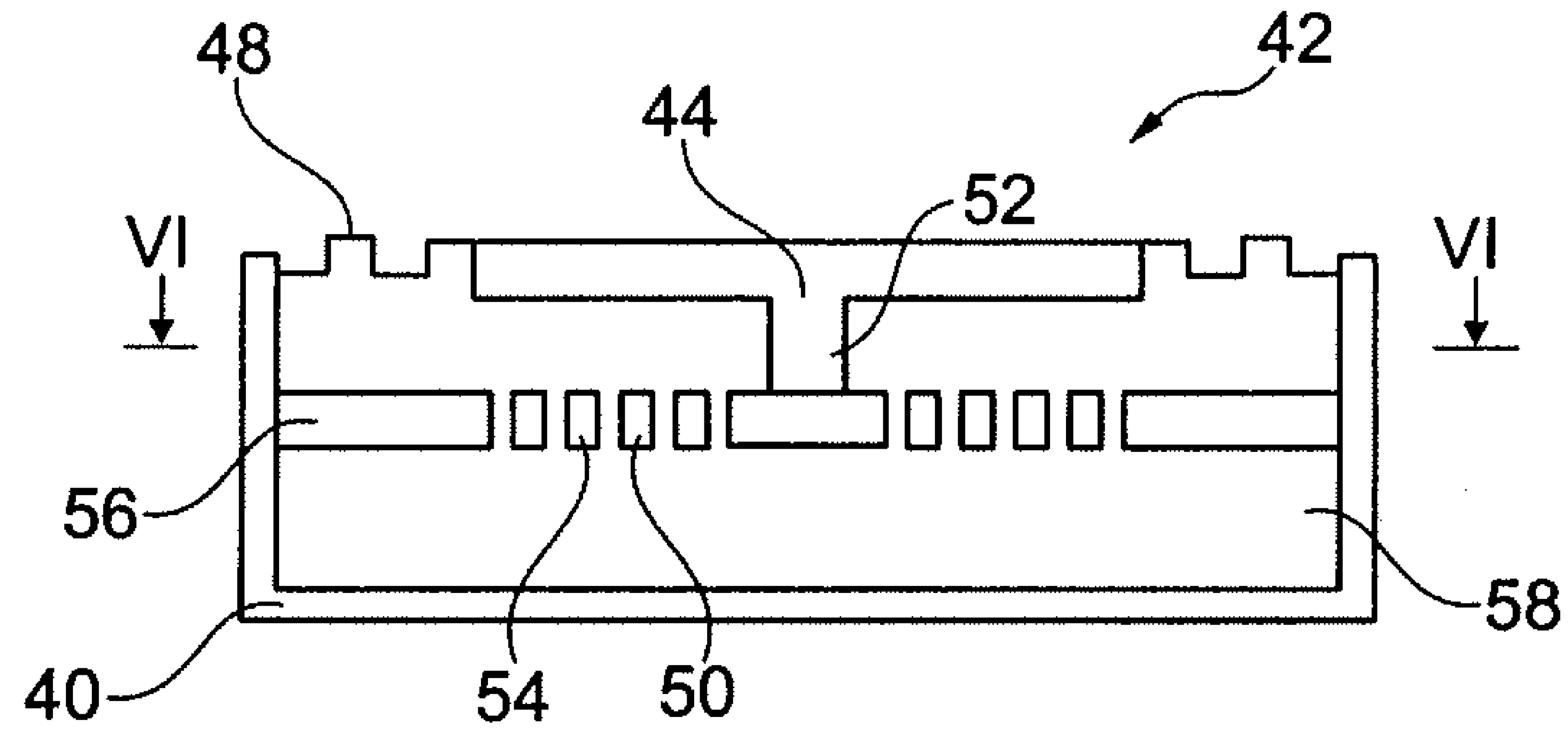


Fig. 5a

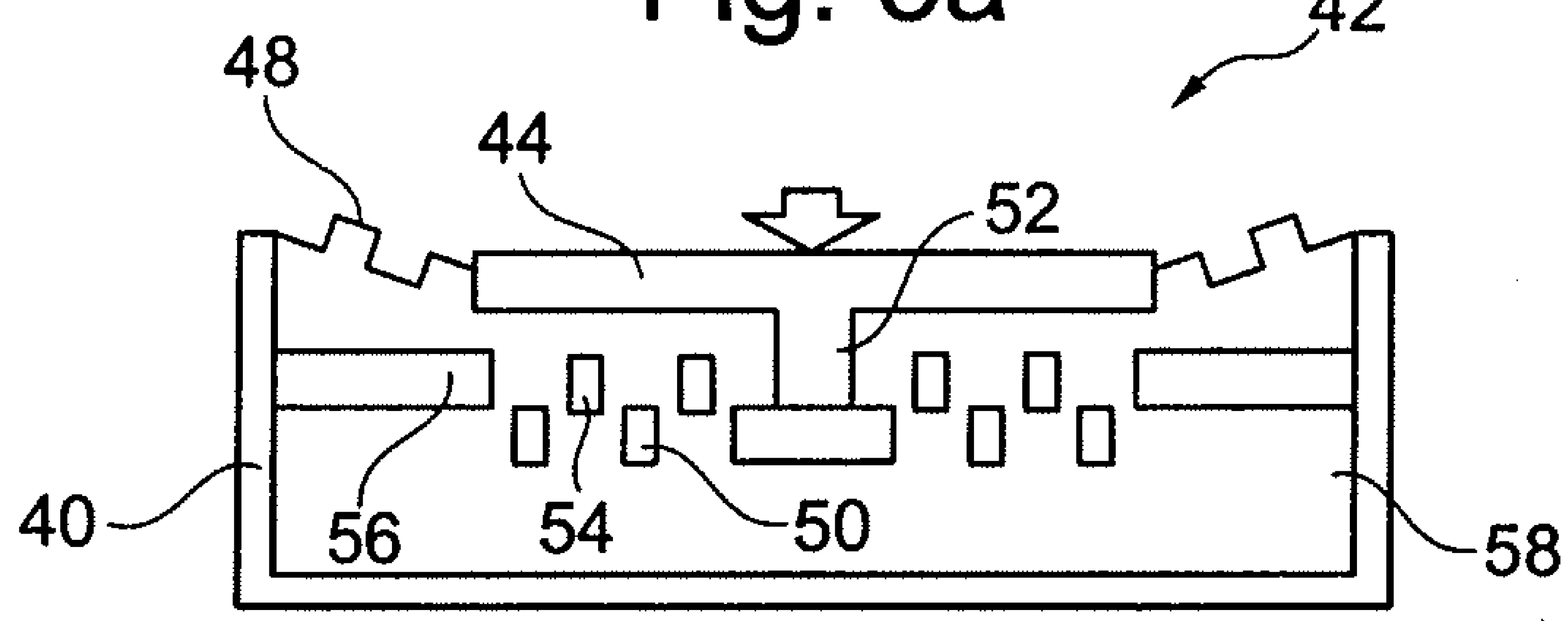


Fig. 5b

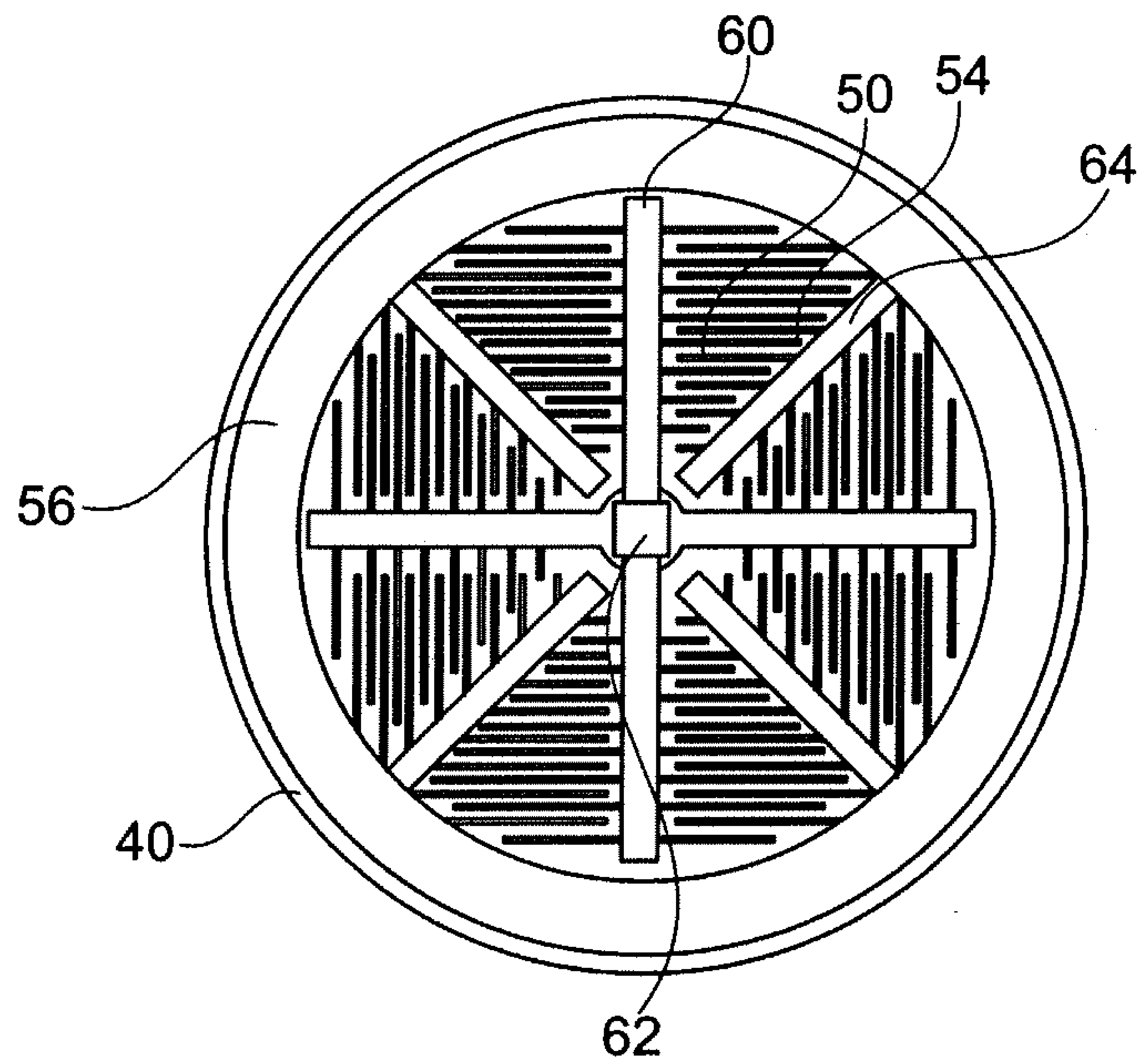


Fig. 6

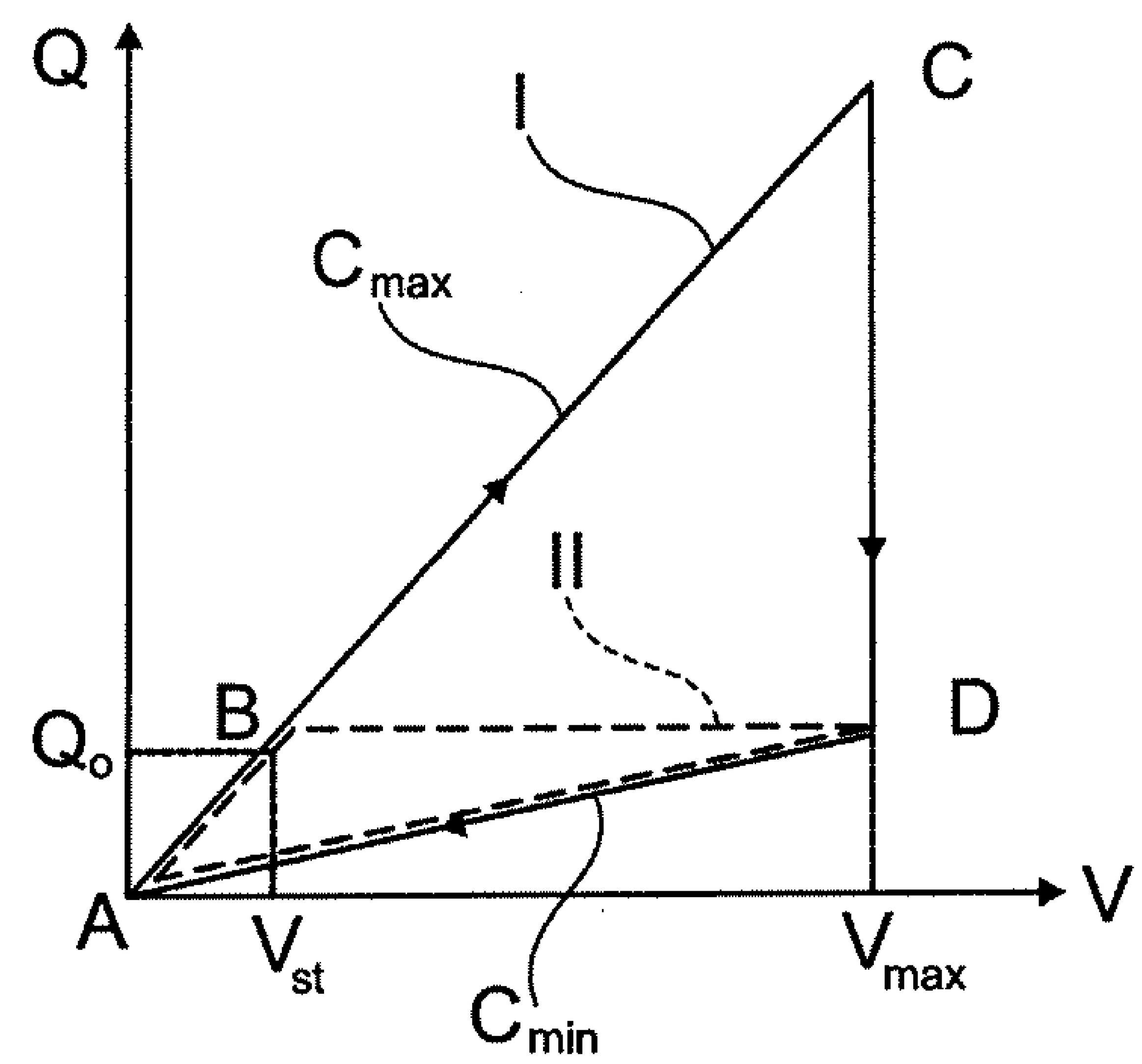


Fig. 7

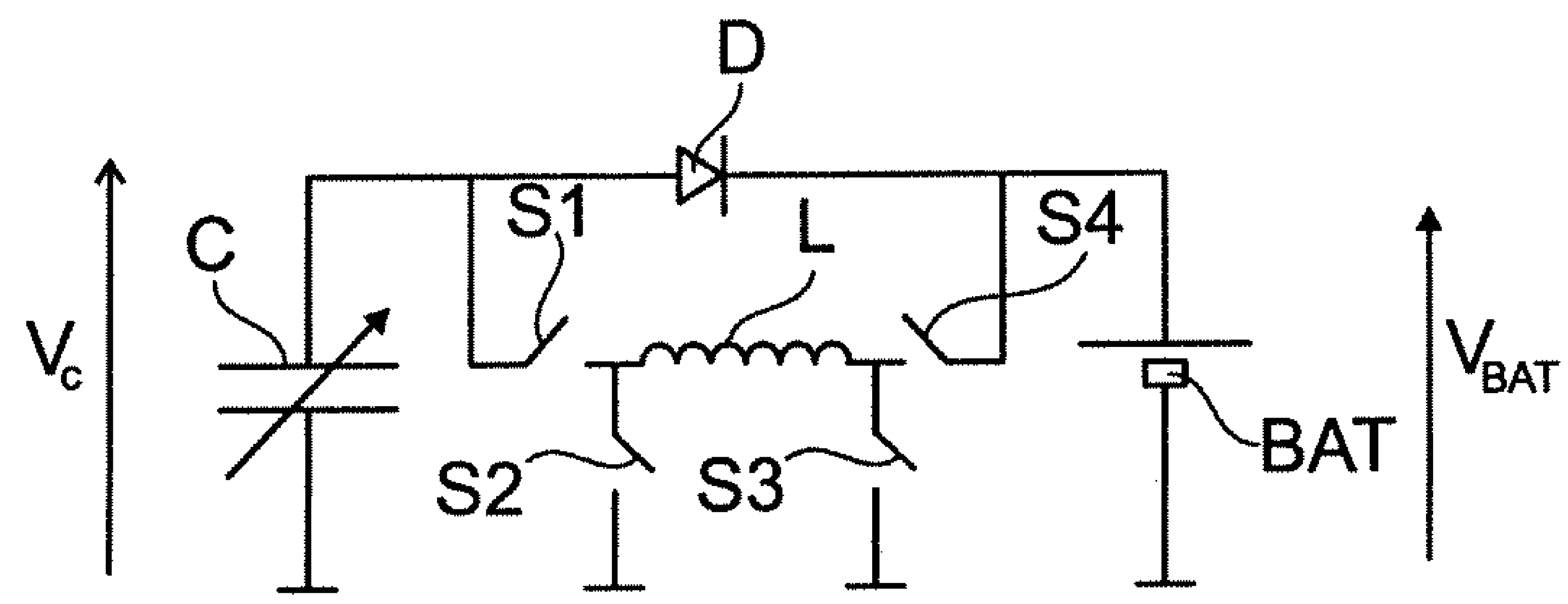


Fig. 8

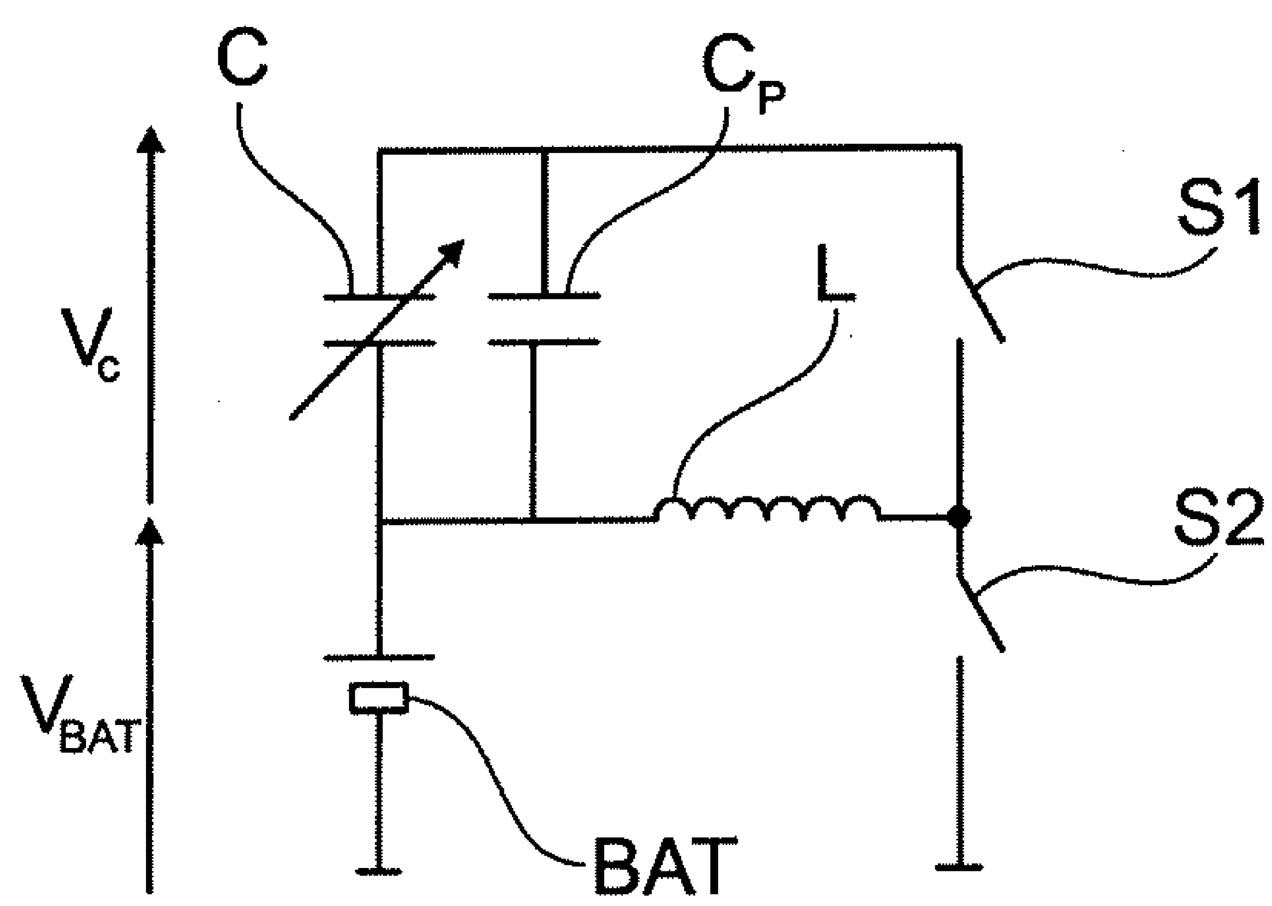


Fig. 9

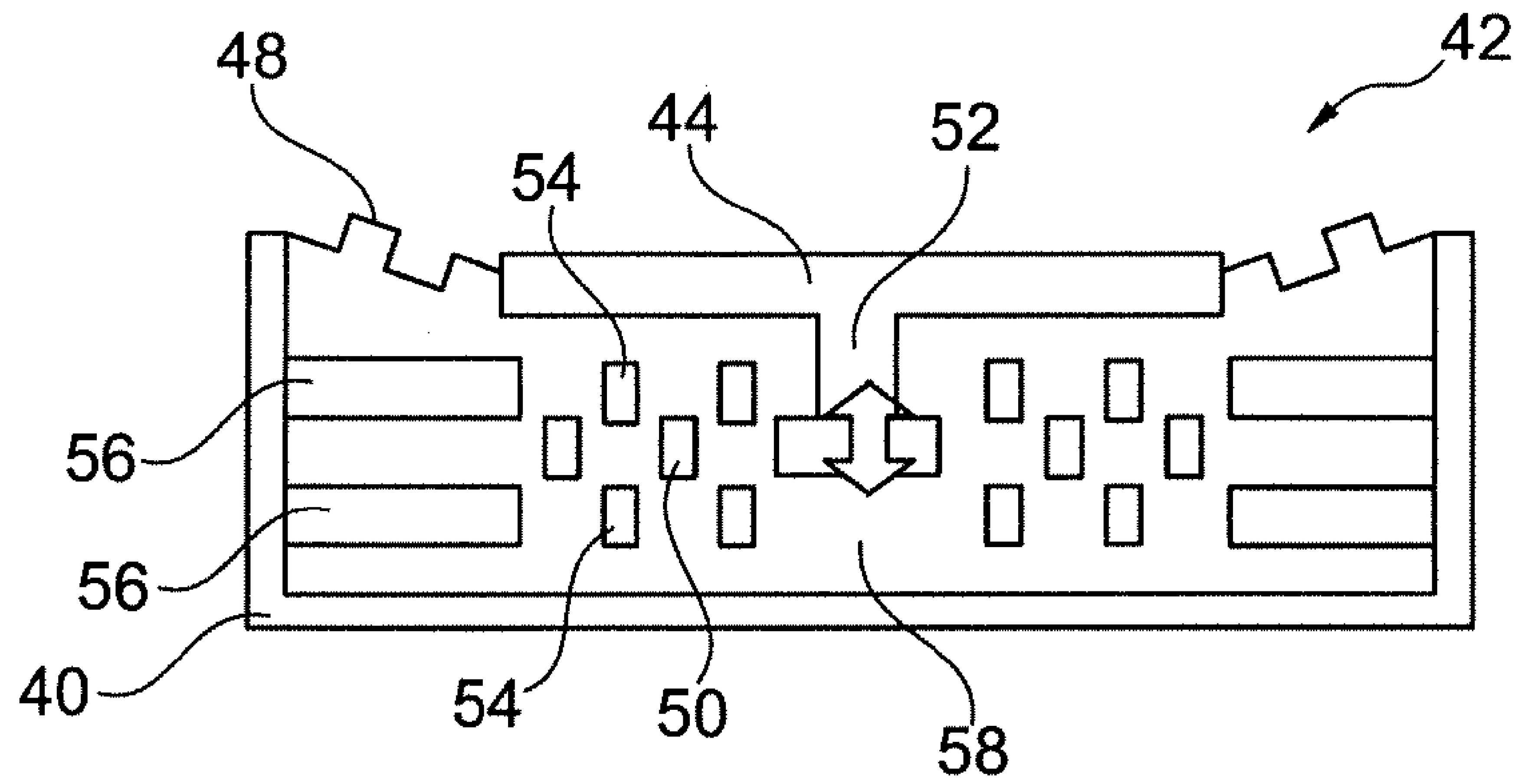


Fig. 10

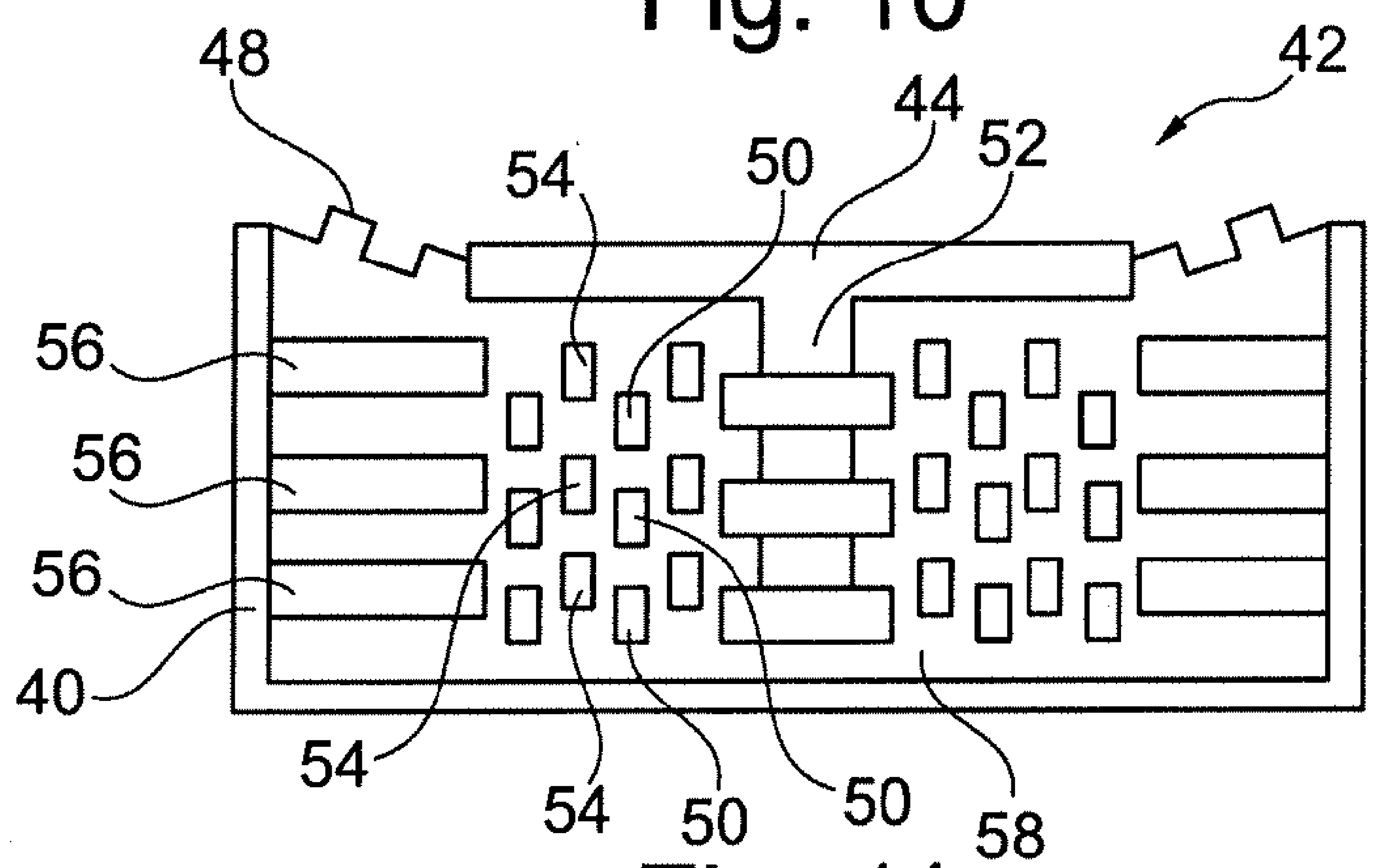


Fig. 11

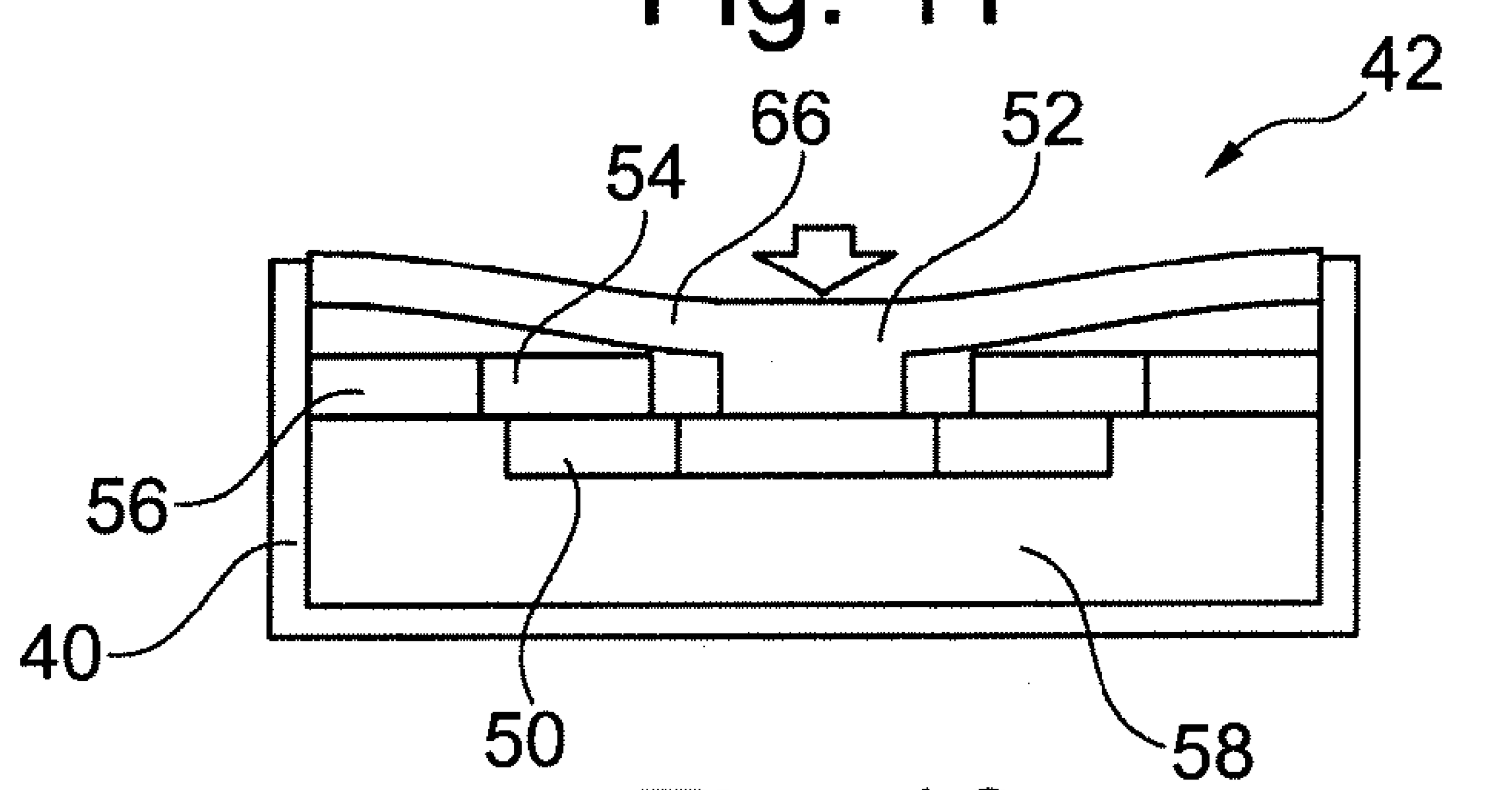


Fig. 12

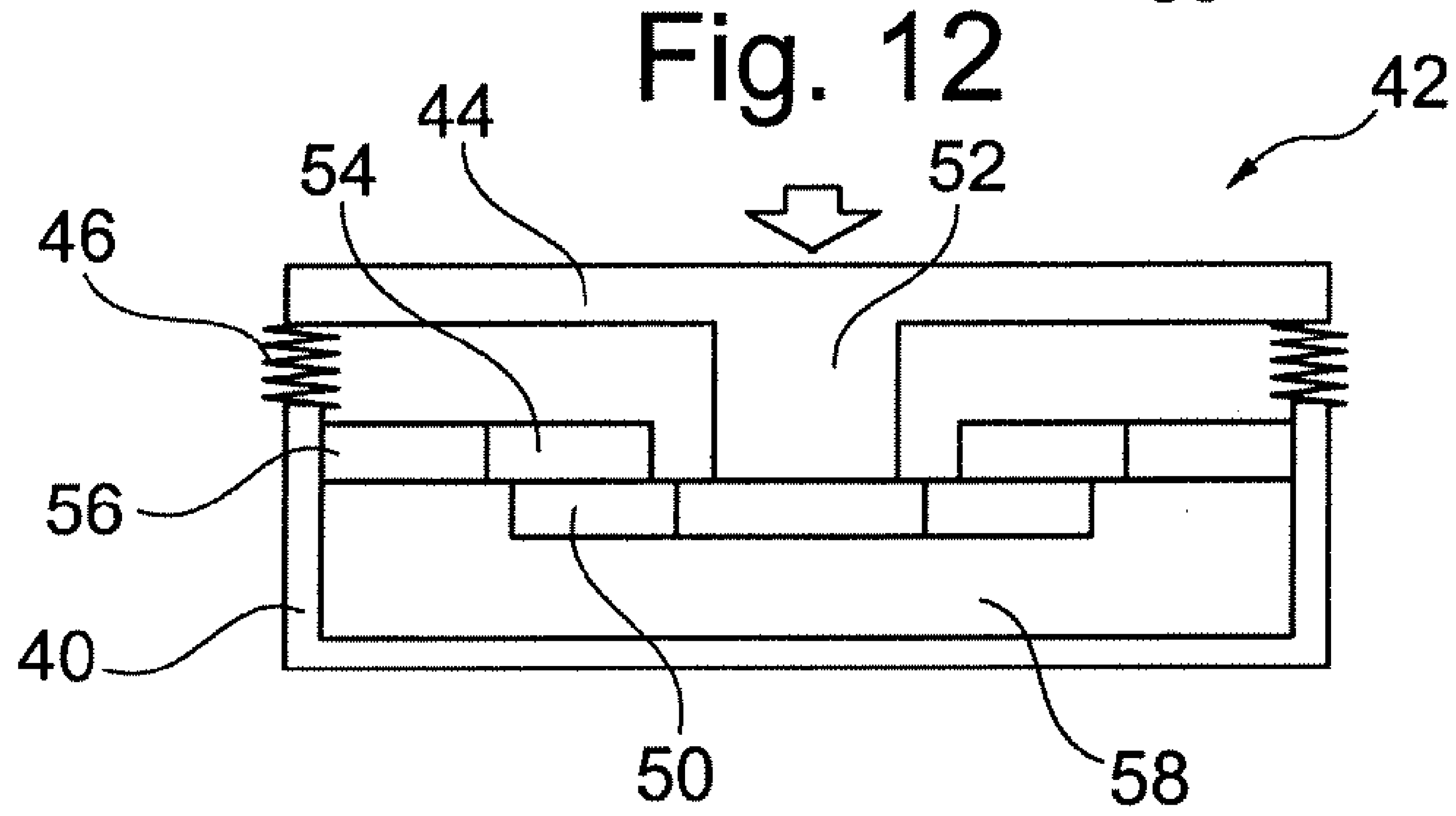


Fig. 13

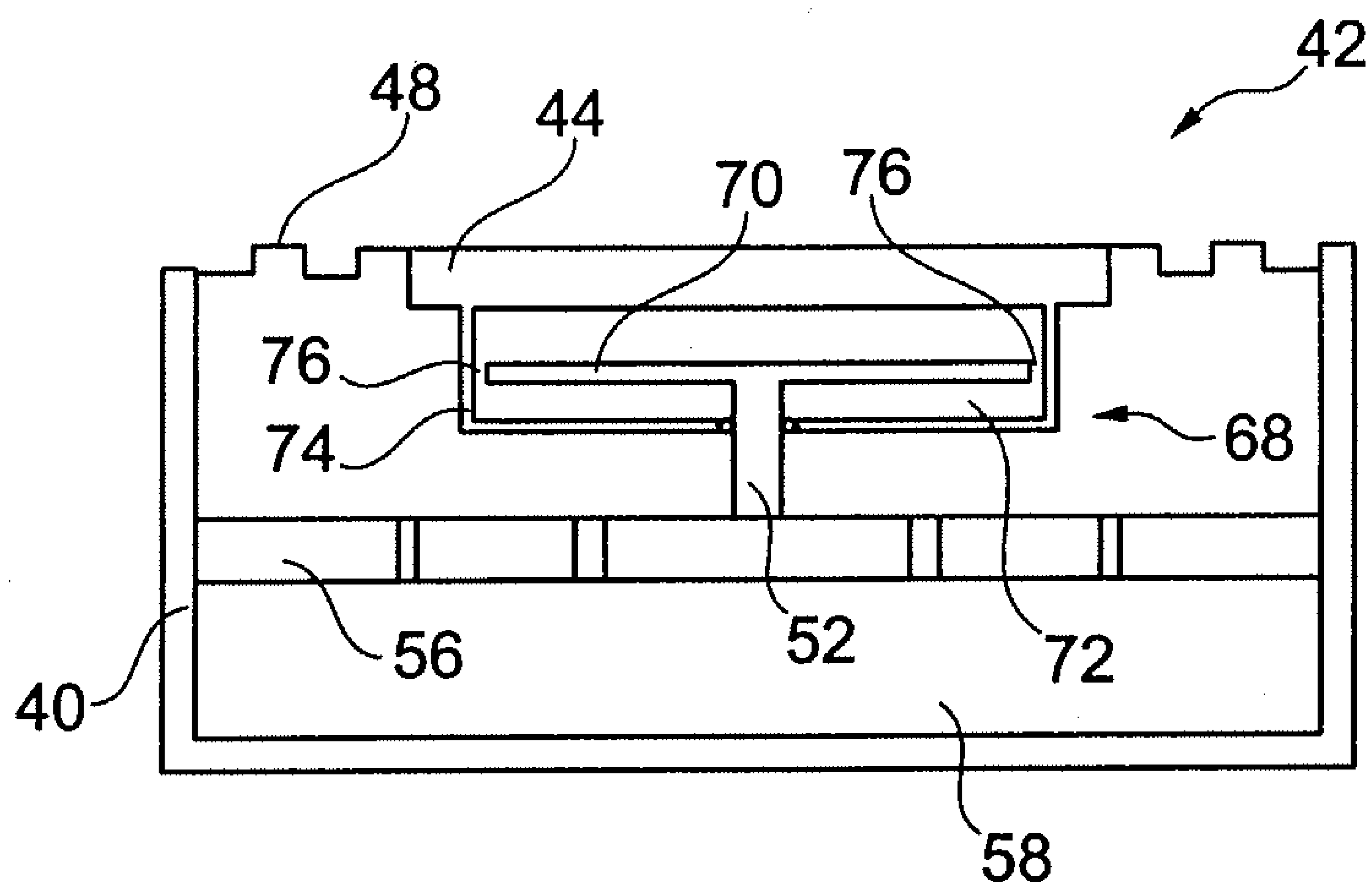

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Fig. 14

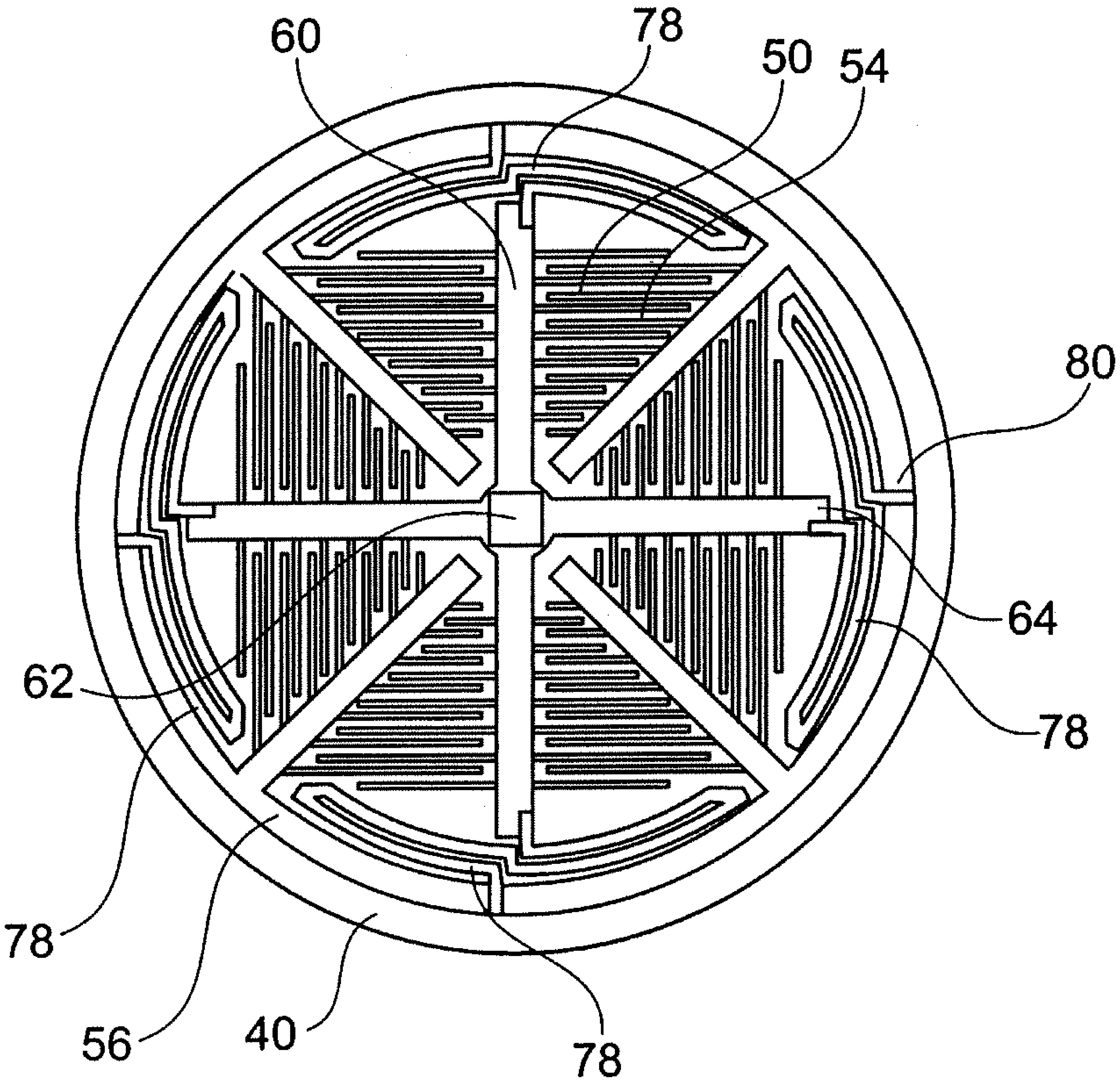
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Fig. 15

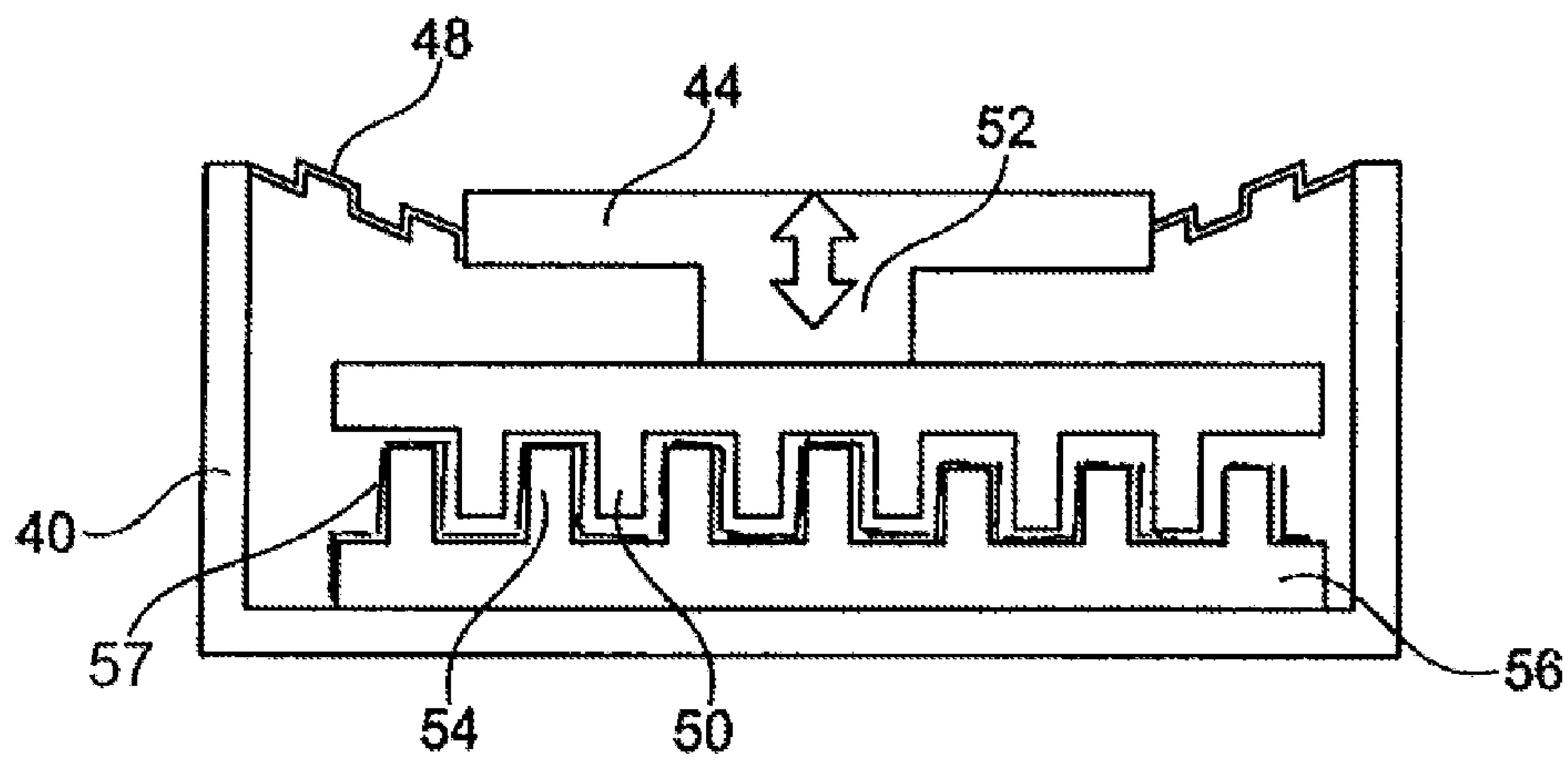

FIG. 16

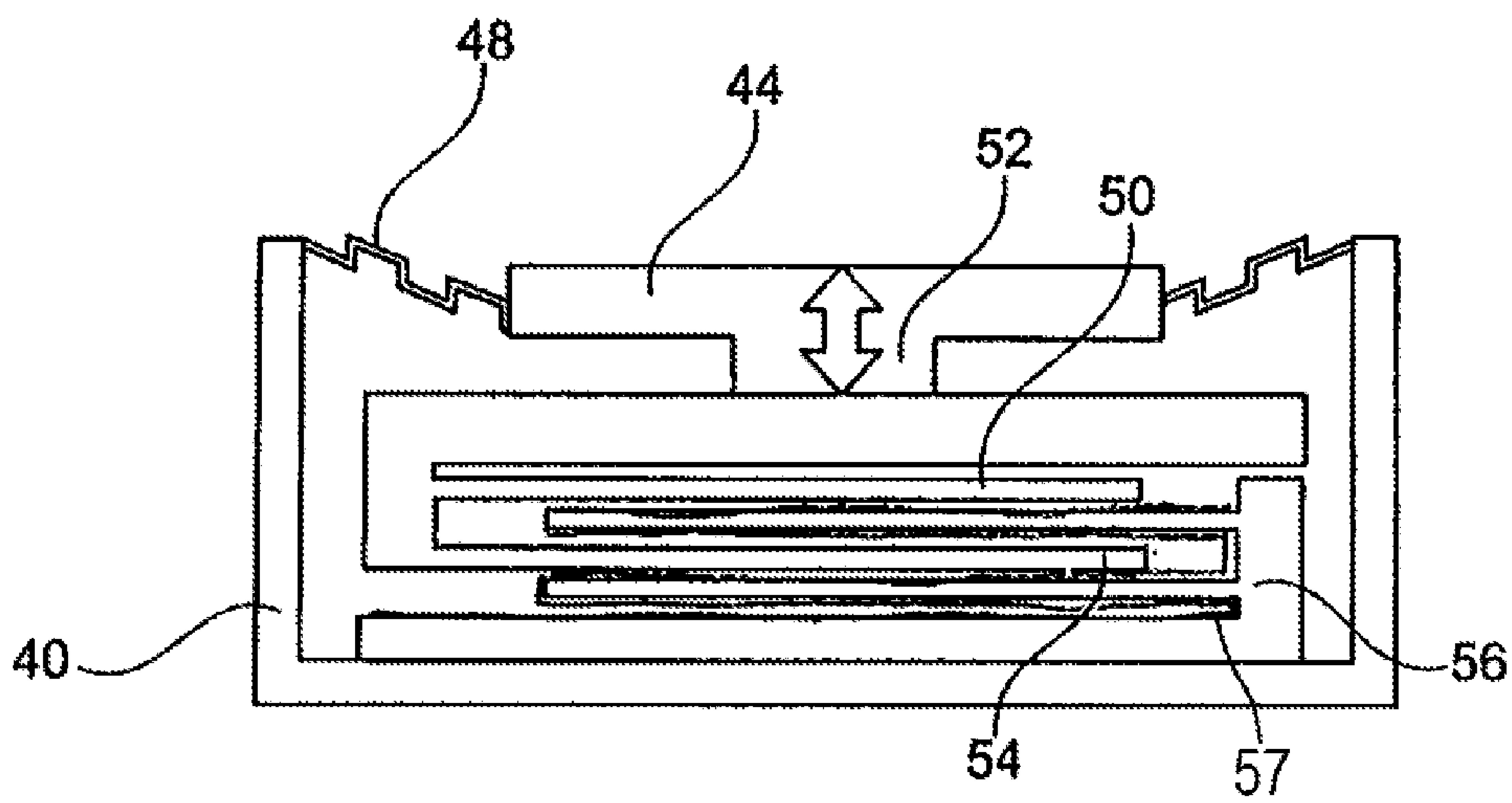

FIG. 17

ENERGY HARVESTER DEVICE FOR AUTONOMOUS INTRACORPOREAL CAPSULE

CROSS-REFERENCE TO RELATED PATENT APPLICATIONS

[0001] This application is a continuation of U.S. application Ser. No. 13/464,795, filed May 4, 2012, which claims the benefit of and priority to French Application No. 11/53790, filed May 4, 2011, both of which are hereby incorporated by reference herein in their entireties.

TECHNICAL FIELD

[0002] The present invention relates to the field of "medical devices" as defined by the Jun. 14, 1993 directive 93/42/CE of the European Communities, and more particularly to the "active implantable medical devices" as defined by the of Jun. 20, 1990 directive 90/385/CEE of the European Communities. Such devices in particular include implantable medical devices that continuously monitor a patient's cardiac rhythm and deliver if necessary to the heart electrical pulses for cardiac stimulation, resynchronization, cardioversion and/or defibrillation in case of a rhythm disorder detected by the device. Such devices also include neurological devices, cochlear implants, etc., as well as devices for pH measurement or devices for intracorporeal impedance measurement (such as the measure of the transpulmonary impedance or of the intracardiac impedance). The invention relates even more particularly to those devices that implement autonomous implanted capsules and are free from any physical connection to a main implanted device (for example, the can of a stimulation pulse generator).

BACKGROUND

[0003] Autonomous implanted capsules are referred to as "leadless capsules" to distinguish them from the electrodes or sensors placed at the distal end of a lead, which lead is traversed throughout its length by one or more electrical conductors connecting by galvanic conduction the electrode or the sensor to a generator connected at the opposite, proximal end, of the lead.

[0004] Such leadless capsules are, for example, described in U.S. Patent Pub. No. 2007/0088397 A1 and WO 2007/047681 A2 (Nanostim, Inc.) and U.S. Patent Pub. No. 2006/0136004 A1 (EBR Systems, Inc.).

[0005] These leadless capsules can be epicardial capsules, which are typically fixed to the outer wall of the heart, or endocardial capsules, which are typically fixed to the inside wall of a ventricular or atrial cavity, by means of a protruding anchoring helical screw, axially extending from the body of the capsule and designed to penetrate the heart tissue by screwing to the implantation site.

[0006] In one embodiment, a leadless capsule includes detection/stimulation circuitry to collect depolarization potentials of the myocardium and/or to apply pacing pulses to the site where the leadless capsule is located. The leadless capsule then includes an appropriate electrode, which can be included in an active part of the anchoring screw.

[0007] It can also incorporate one or more sensors for locally measuring the value of a parameter such as the oxygen level in the blood, the endocardial cardiac pressure, the acceleration of the heart wall, the acceleration of the patient as an indicator of activity, etc. Of course, the leadless capsules incorporate transmitter/receiver means for wireless communication, for the remote exchange of data.

[0008] The present invention is nevertheless not limited to a particular type of leadless capsule, and is equally applicable to any type of leadless capsule, regardless of its functional purpose.

[0009] Whatever the technique implemented, the signal processing inside the leadless capsule and the remote transmission of data into or out of the leadless capsule requires a non-negligible energy supply as compared to the energy resources a leadless capsule can store. However, due to its autonomous nature, the leadless capsule can only use its own resources, such as an energy harvester circuit (responsive to the movement of the leadless capsule), associated with an integrated small buffer battery. The management of the available energy is thus a crucial point for the development of autonomous leadless capsules and their capabilities, especially their ability to have an integrated self-power supply system.

[0010] Various techniques of energy harvesting have been proposed, adapted to leadless autonomous implants. U.S. Patent Pub. No. 2006/0217776 A1, U.S. Pat. No. 3,456,134 A and WO 2007/149462 A2 describe systems using piezoelectric transducers directly transforming into electrical energy the movement of a mass resulting from the acceleration of the patient's organs or body. However, given the relatively low excitation frequencies (below 10 Hz), the excursions of the movements are relatively large, which does not allow a for significant miniaturization. In addition, since these excitations do not have stable specific frequencies, the piezoelectric generator cannot operate in a resonant mode, and thereby loses much of its effectiveness.

[0011] Other devices have been proposed to transform pressure changes occurring within the body into electricity, including changes in blood pressure or those resulting from the movements of the patient's diaphragm during breathing. This transformation is effected by means of a magnetic microgenerator, functioning as an alternator or as a dynamo, by variations in magnetic flux induced in a coil. Reference is made to U.S. Patent Pub. No. 2005/0256549 A1, GB 2350302 A, U.S. Patent Pub. Nos. 2008/0262562 A1 and 2007/0276444 A1. Due to the presence of moving parts, however, the complexity of the design of the mechanical and electrical parts and their relatively large volume effectively limit, the miniaturization and the overall reliability of such a generator. Moreover and most importantly, such a generator is inherently sensitive to external magnetic fields and is not compatible with the magnetic resonance imaging systems (MRI) because of the very high static magnetic fields generated by these systems, typically in the order of 0.5 to 3 T or more.

[0012] It also has been proposed to use an electrostatic transducer made of electrodes modeling a capacitor, for example, with a set of combs and interdigitated-counter combs. One of the electrodes is secured to a support fixed on the body of the case, the other being coupled to an oscillating mass called "seismic mass". This mass is set in motion by movement of the entire system including the transducer, and it carries with it one of the electrodes of the transducer, which thus move relative to the other by a variation of the dielectric gap and/or of the facing surfaces of the two electrodes. If the capacitor is initially pre-loaded with an energy charge, or if the structure includes electrets (or electrets films) to maintain a continuous load, the capacity variation causes an energy increase in this capacitor that can be extracted by an electronic circuit and then stored in a buffer battery. The mechanical energy collected by the oscillating mass can thus almost entirely be converted into electrical energy in a single cycle. This technique is described, for example, by F. Peano and T. Tambosso, *Design and Optimization of a MEMS Electret-Based Capacitive Energy Scavenger*, Journal of Microelectromechanical Systems, 14 (3), 429-435, 2005, or S. Meninger et al. *Vibration-to-Electric Energy Conversion*, IEEE Transactions on Very Large Scale Integration (VLSI) Systems, vol. 9, no. 1, pp. 64-76, 2001. This type of transducer has the same drawbacks, however, as the piezoelectric transducers because of limitations imposed by the oscillating mass, both in terms of miniaturization (the seismic mass is relatively large) and efficiency with respect to the driving movements. Indeed, the relatively low excitation frequencies (below 10 Hz) involve relatively large excursions and/or a relatively high mass of the oscillating element, which does not allow a significant miniaturization.

[0013] Another known energy harvester system, without an oscillating weight, is disclosed by U.S. Patent Pub. No. 2009/021292A1. This document discloses an energy harvesting power system incorporated into an implantable capsule in which the housing body has a deformable element resulting from changes in pressure of the surrounding environment. The deformation of this element is transmitted to an electrostatic transducer directly converting the mechanical energy of deformation into electrical energy, which is then delivered to a power management and storage module powering the device with energy. Note that such a system does not need to be resonant or to contain magnetic elements. However, the system described utilizes pressure variations that result at least partly from mechanical forces applied to the capsule, under the effect of contact forces with the surrounding tissues or deformation thereof. Thus, in the case of a system that is fully submerged in a body fluid (for example such an energy harvesting system used in an intracardiac capsule blood pressure changes during rapid changes in the systole-diastole cycle), the slow variations of atmospheric pressure disrupt the operation of the energy harvesting system: indeed, as the capsule is strictly waterproof, its interior volume is initially at the pressure defined during manufacturing and the equilibrium point at rest of the deformable element is offset compared to the nominal rest position if the atmospheric pressure varies.

SUMMARY

[0014] It is therefore an object of the present invention is to provide an improved power generator for an implantable autonomous leadless capsule.

[0015] It is another object to provide an energy harvesting circuit that ensures that changes in a patient's systole-diastole cardiac cycle are fully transmitted to the electrodes around the same nominal rest point.

[0016] Broadly, the present invention relates to an autonomous intracorporeal leadless capsule of a type similar to that described in the aforementioned U.S. Patent Pub. No. 2009/021292 A1, including a body and, within the body, electronic circuits and a power supply including:

[0017] an energy harvester transducer, for converting an external physical stress applied to the capsule to an electrical quantity, this transducer comprising:

[0018] a first capacitor electrode, coupled with a movable actuator receiving said external physical stress, the movable element of actuation of the transducer being substantially free of an oscillating weight and comprising a deformable surface, formed on the exterior of the capsule body and being alternately deformed in one direction and in the other under the effect of pressure variations in the surroundings of the capsule; and

[0019] a second capacitor electrode, mounted on a support connected to a region of the body other than the movable actuator, the two electrodes having facing surfaces separated by a dielectric gap together defining a capacitor (C), and said physical stress producing a consequential modification of said facing surfaces and/or of said dielectric gap with correlative variation of the capacity of said capacitor; and

[0020] a storage and power management circuit, powered by the energy harvester transducer as a result of a decrease of the distance between the facing surfaces and/or of an increase the dielectric gap of the capacitor.

[0021] Both electrodes have facing surfaces separated by a dielectric together defining a capacitor, and the deformation of the deformable surface produces a corresponding modification of said facing surfaces and/or of said dielectric gap with correlative variation of the capacity of the capacitor. In addition, the management module includes a means for preloading a charge on the capacitor when its capacity is maximum, and of unloading the capacitor by transferring its energy changes to a storage device when this capacity decreases as a result of a decrease of the distance between the facing surfaces and/or of an increase of the dielectric gap of the capacitor.

[0022] Preferably, the deformable surface is coupled to the first electrode with the interposition of a damping element forming a mechanical high-pass filter with respect to pressure variations in the medium surrounding the capsule.

[0023] In one embodiment, the deformable surface has a rigid surface coupled to the first electrode and an elastically deformable structure, such as a bellows or other organ, for connecting the rigid surface to the body, or to a membrane coupled to the first electrode in a region of greater deformation of the latter.

[0024] In one embodiment, the first and second capacitor electrodes are advantageously made in the form of combs and interdigitated counter-combs, and the first capacitor electrode can be coupled to the body of the capsule by an elastically deformable support forming a guiding spring.

[0025] The leadless capsule may further comprise means for preloading the capacitor when its capacity is maximum, and for unloading it by transferring its stored energy to a storage device, e.g., a suitable battery or other device, when that capacity decreases as a result of a decrease in space between the facing surfaces and/or of an increase in the dielectric gap of the capacitor.

[0026] Advantageously, the present invention provides for improved miniaturization: compatibility with the extremely small volume (a few cubic millimeters) of a leadless implant;

[0027] Advantageously, the present invention provides for improved reliability: guaranteed secured operation over several years of lifetime of the implant;

[0028] Advantageously, the present invention provides for improved insensitivity to magnetic phenomena, including MRI compatibility which is now required for implanted devices;

[0029] Advantageously, the present invention provides for improved biocompatibility: absence of external elements that can cause inflammatory reactions.

BRIEF DESCRIPTION OF THE DRAWINGS

[0030] Further features, characteristics and advantages of the present invention will become apparent to a person of ordinary skill in the art from the following detailed description of preferred embodiments of the present invention, made with reference to the drawings annexed, in which like reference characters refer to like elements, and in which:

[0031] FIG. **1** schematically illustrates a set of medical devices including leadless capsules, implanted within the body of a patient;

[0032] FIG. **2** is a functional block diagram showing the various components of a leadless capsule;

[0033] FIGS. **3** and **4** illustrate respectively two embodiments of a body of leadless capsule of the present invention;

[0034] FIGS. **5***a* and **5***b* are schematic sectional views of a first embodiment of an electrostatically energy harvesting leadless capsule of the present invention;

[0035] FIG. **6** is a plan view taken along line VI-VI of FIG. **5***a*, of the first embodiment of the electrostatically energy harvesting leadless capsule;

[0036] FIG. **7** is a load/voltage diagram illustrating two methods to operate the energy harvesting circuit, at constant load or at constant voltage, respectively;

[0037] FIG. **8** is a schematic representation of an energy harvester circuit with constant voltage;

[0038] FIG. **9** is a schematic representation of an energy harvester circuit at constant load;

[0039] FIG. **10** illustrates a second embodiment of an electrostatically energy harvesting leadless capsule of the present invention, for energy harvesting in both directions of movement of the movable electrode;

[0040] FIG. **11** illustrates a third embodiment of an electrostatically energy harvesting leadless capsule, of the present invention using a stack of structures such as that illustrated in FIG. **5***a* for the first embodiment;

[0041] FIG. **12** illustrates a fourth embodiment of an electrostatically energy harvesting leadless capsule, wherein the deformable element is a flexible membrane;

[0042] FIG. **13** illustrates a fifth embodiment of an electrostatically energy harvesting leadless capsule, using a bellows for connecting the movable element to the body of the capsule;

[0043] FIG. **14** illustrates an embodiment of a leadless capsule according to the present invention, applicable to the various embodiments described above, that eliminate the effects of the slow variations of pressure;

[0044] FIG. **15** illustrates an embodiment of an electrostatically energy harvesting leadless capsule, using photolithographic technology to produce fixed combs and movable counter-combs suspended by guiding springs; and

[0045] FIGS. **16** and **17** illustrate two alternative embodiments of the capacitor structure, particularly adapted to the use of armatures carrying electrets.

DETAILED DESCRIPTION

[0046] With reference to the drawing FIGS. **1-17**, various examples of preferred embodiments of an electrostatically energy harvesting capsule will be described.

[0047] With reference to FIG. **1**, a set of medical devices implanted in the body of a patient is shown. This set is equipped with a device **10** such as an implantable defibrillator/pacemaker/resynchronizer, a subcutaneous defibrillator or a long-term recorder. Device **10** is deemed the master device of a network comprising a plurality of slave devices **12** to **18**, which may include intracardiac **12** or epicardial **14** leadless capsules located directly on the patient's heart, other devices **16** such as myopotential sensors or neurological stimulation devices, and optionally an external device **18** disposed on armlets and provided with electrodes in galvanic contact with the skin.

[0048] Main device **10** also can be used as a gateway to the outside world to communicate via telemetry with a compatible external device **20** such as a programmer or a device for remote transmission of data.

[0049] With reference to FIG. **2**, an internal circuit of the implanted autonomous leadless capsules **12** to **16** is illustrated. The leadless capsule contains, for example, a pair of electrodes **22**, **24** connected to a pacing pulse generator circuit **26** (e.g., for an active leadless capsule incorporating this function) and/or a detection circuit **28** for the collection of depolarization potentials collected between the electrodes **22** and **24**. A central circuit **30** includes all the electronics required to control the various functions of the capsule, the storage the collected signals, etc. It comprises a microcontroller and an oscillator generating the clock signals needed for the operation of the microcontroller and for the communication. It may also contain an analog/digital converter and a digital storage memory. The capsule may also be provided with a sensor **32** such as, for example, an acceleration sensor, a pressure sensor, a hemodynamic sensor, a temperature sensor, and an oxygen saturation sensor. The leadless capsule also include an energy harvester circuit **34** powering all circuits via an energy management circuit **36**. The electrodes **22** and **24** are also connected to a pulse transmission/reception circuit **38** used for wireless communication with the master device or the other leadless capsules.

[0050] The present invention more particularly relates to the energy harvester circuit **34** which, typically, uses the pressure variations of the surrounding environment, including the cyclic variations of blood pressure, to move an electrode of a capacitor element relatively to another electrode positioned vis-à-vis (i.e., facing) one another. The energy harvesting is obtained by the variation of capacity of the capacitor resulting from the relative displacement of the two electrodes, which causes a change in the spacing between their facing surfaces and/or a variation of the dielectric gap that separates them.

[0051] To take into account these deformations, preferably the capsule is provided in the form of a body **40**, as shown in FIGS. **3** and **4**, with one or more deformable elements **42** operating at the rhythm caused by the changes in the pressure of the fluid in which the capsule is immersed (typically, the variations of blood pressure, in the case of a cardiac capsule). Deformable element **42** includes a rigid surface **44** which is effected by the pressure exerted, and is connected to the rest of the body by a deformable bellows **46**, which moves in response to the effect of the external forces to which rigid surface **44** is exposed.

[0052] With reference to the embodiment illustrated in FIG. **3**, this surface/bellows assembly **44**, **46** is disposed on an axial end face of the capsule **40**, which has a generally cylindrical shape. Dimensions are typically about 6 mm in diameter for a length of 20 mm, and provides a very small volume of about 0.5 cm^3.

[0053] With reference to the embodiment illustrated in the FIG. **4**, two deformable sets **42** are arranged on side faces of the body **40** of the leadless capsule. Rigid surfaces **44** are connected to block **40** by bellows **46**, with surfaces **44** arranged parallel to each other and to the main axis of the capsule. In this embodiment the energy harvesting system is split; it also frees the two axial ends of the capsule, which can be important, particularly to place an anchoring screw system with no obstacles to this configuration due to the energy harvesting system.

[0054] In one embodiment, the body **40** and its deformable element **42** are advantageously made in a monobloc form, for example, of evaporated titanium or electrodeposited on a soluble stylet.

[0055] With reference to FIGS. **5***a*, **5***b* and **6**, a first embodiment of an electrostatically energy harvesting capsule will be described here to illustrate the principle of the electrostatic transducer with a variable capacitor.

[0056] In this first embodiment, deformable element **42** includes a planar rigid surface **44** coupled to body **40** of the capsule by an elastic element **48**, preferably formed of peripheral ripples around rigid surface **44**. Rigid surface **44**, which is movable under the effects of the pressure variations of the surrounding environment, is connected to a series of first capacitor electrodes **50** via the coupling element **52**, which is simply shown here as a rod. As can be seen particularly in FIG. **4**, electrodes **50** are preferably configured in the form of combs made, for example, by conventional photogravure (photolithography). The device also comprises second electrodes **54**, for example, made in the form of counter-combs interdigitated with the combs of electrodes **50** (cf. FIG. **6**), connected to the body **40** by a peripheral support **56**. The assembly formed by electrodes **50**, **54** is enclosed in a sealed volume **58** formed by body **40** closed by deformable member **42**.

[0057] This provides a transducer that can be modelled by a variable capacitor comprising:

[0058] A first suspended electrode, incorporated by the combs **50** which are mechanically and electrically gathered by arms **60** and central support **62** connected to movable surface **44**;

[0059] A second fixed electrode, constituted by the counter-combs **54** mechanically and electrically gathered together by the fixed arms **64** themselves attached to the body **40** via the annular support **56**; and

[0060] A dielectric gap, defined between the two electrodes.

[0061] With the combs and the interdigitated counter-combs, as illustrated FIG. **6**, in the case of a depression of deformable element **42**, the air gap and the overlap in the plane of the combs remain constant, but the vertical overlap changes during the movement. The capacity is maximum when the two structures (combs and counter-combs) are vertically at the same level, and is minimal (close to zero) when the movable structure (suspended combs **50**) have moved by a distance equal to their thickness (as shown in FIG. **5***b*), having thus rendered almost null the facing surfaces of the combs with the counter-combs.

[0062] Concretely, when external pressure is exerted on movable surface **44**, for example, during the systole in the case of a leadless capsule immersed in a blood medium, the pressure variation produces a depression of surface **44** towards the inside the leadless capsule, as shown in FIG. **5***b*. Combs **50** of the movable electrode then move away from fixed combs **54** of the fixed capacitor electrode and produce a variation in the capacity of the capacitor, in this case a decrease in that capacity because of the decrease of the facing surfaces of the stationary and movable electrodes and of the increase in the dielectric gap between these surfaces.

[0063] If the capacitor had previously been preloaded, the decrease in the capacity of the capacitor produces an energy excess which may be discharged by appropriate circuits to a storage device, and thus allows, at each systolic cycle, to recover an amount of energy that is eventually sufficient to ensure continuous operation of the electronic circuits of the leadless capsule without any additional energy contribution.

[0064] The preload of the capacitor can be performed by specific circuits, described below with reference to FIGS. **7**-**9**.

[0065] In one embodiment, the preload can be achieved by annexed piezoelectric elements, which during the initial pressure variations deform and generate a voltage precharging the capacitor during its start-up, according to a technique notably described by Khbeis & al., *Design of a Hybrid Ambient Low Frequency, Low Intensity Vibration Energy Scavenger*, the Sixth International Workshop on Micro and Nanotechnology for Power Generation and Energy Conversion Applications, Berkeley, 2006, or in FR 2896635 A1.

[0066] In yet another embodiment, the preload can be avoided by having an electret structure on one side of the capacitor, these electrets generating the required electric field. This particular technique is described in the cited article Peano Tambosso discussed above, or by Sakane & al., *The Development of a High-Performance Perfluorinated Polymer Electret and Its Application to Micro Power Generation*, Journal of Micromechanics and Microengineering, Vol. 18, pp. 1-6, 2008.

[0067] With reference to FIGS. **7**-**9**, an embodiment of a method to harvest the energy through the change in the capacity of the capacitor is illustrated. Two techniques for recovery, respectively at constant voltage and constant load, will now be described. The diagram in FIG. **7** illustrates two charge/voltage characteristics for a full charge/discharge cycle of the variable capacitor. The characteristic I corresponds to a cycle following the path ACDA at constant voltage. The capacitor is initially charged to the maximum voltage V_{max} (segment AC), while the capacity is maximum ($C=C_{max}$). This load is operated in a sufficiently short time (typically less than a microsecond) for this capacity to be considered constant. During the movement of the movable element, the capacity is reduced from C_{max} to C_{min}, the voltage being held constant (by hypothesis) and maintained at Vmax, the characteristic follows the segment CD.

[0068] During this phase, the energy stored in the capacitor is transferred to the storage device. The residual charge Q_0 is then harvested by following the DA segment, with $C=C_{min}$. The total harvested energy is the area of the cycle I, $\frac{1}{2}(C_{max}-C_{min})V_{max}^2$.

[0069] In the case of a conversion at constant load (characteristic II following the path ABDA), the capacitor is initially charged to a starting voltage V_{st}, with a maximum capacity $C=C_{max}$ (segment AB).

[0070] The circuit is then left open (constant load Q_0) during the movement of the electrodes of the capacitor, which decreases the capacity from its maximum value C_{max} to its minimum value C_{min} (segment BD), the voltage increasing to its maximum value V_{max} for satisfying the equation Q=CV. The load is then returned (segment AD), in the same method as before. The total harvested energy is equal to the area of the cycle II, $\frac{1}{2}(C_{max}-C_{min})V_{st}V_{max}$. This value is, for the same maximum voltage V_{max}, lower than that of the solution at constant voltage (characteristic I); however, this solution may provide additional benefits, including the ability to operate with a low initial voltage. It is also possible to provide an additional capacitor, connected in parallel with the variable capacitor C, to increase the energy and thus reach closer performance to the solution at constant voltage.

[0071] FIG. **8** schematically illustrates an exemplary circuit for energy harvesting at constant voltage. This circuit configuration is in itself known, and for details one can refer, for example, to E. Torres and G. Rincon-Mora, *Electrostatic Energy-Harvesting and Battery-Charging CMOS System Prototype*, IEEE Transactions on Circuits and Systems I: Regular Papers, Vol. 56, No. 9, 1938-1948, September 2009.

[0072] Essentially, the four switches S**1** to S**4** are initially open and the circuit monitors the voltage across the capacitor C for detecting when it becomes maximum. At that moment, the preload phase is triggered, starting first of all by loading the inductance L (S**1** and S**3** closed, S**2** and S**4** open), then by discharging this inductance L in the capacitor C (S**1** and S**3** open, S**2** and S**4** closed), all in a very short time with respect to the variation of capacity of the capacitor C. The switches are then opened, and the diode D fixes the voltage across C, by discharging the capacitor into a storage device, preferably a battery BAT, thus loading it.

[0073] FIG. **9** illustrates a circuit diagram of an energy harvesting circuit at constant load. This circuit is also known, and more details can be found in the aforementioned article of S. Meninger et al. *Vibration-to-Electric Energy Conversion*, IEEE Transactions on Very Large Scale Integration (VLSI) Systems, vol. 9, no. 1, p. 64-76, 2001.

[0074] Essentially, the voltage across the capacitors C and Cp (an additional capacitor Cp is optionally added in parallel to C to increase the produced energy) is initially zero. When the control circuit detects the maximum capacity of the capacitor C, S**1** opens and S**2** closes, loading the inductance L, then immediately after S**1** closes and S**2** opens, which transfers energy from L to capacitors C and Cp. Then the two IQ switches S**1** and S**2** open and the capacity of capacitor C declines as a result of mechanical forces, to the minimum value C_{min}. At that moment, S**1** is closed and S**2** remains open, which loads the inductance L from the energy accumulated in the capacitors C and Cp. As soon as the voltage at the terminations of the latter is equal to zero, S**1** opens and S**2** closes, which allows transferring the collected energy from the inductor L to the storage device, preferably battery BAT.

[0075] FIG. **10** illustrates a second embodiment of an electrostatically energy harvesting leadless capsule, wherein the electrode formed by the movable comb **50** is, at rest, positioned between two fixed superimposed counter-combs **54**, so that the movable comb **50** comes next to one or the other of the counter-combs **54** along the direction of movement of the membrane. This allows harvesting the energy when the membrane moves in either direction, for example, during both phases of systole and diastole in the case wherein the leadless capsule is surrounded by a blood medium.

[0076] FIG. **11** illustrates a third embodiment of an electrostatically energy harvesting leadless capsule, wherein the transducer is a multilayer structure as described with reference to FIGS. **5** and **6**, to increase the electrode surface by the further multiplication of the combs/counter-combs sets, which maximizes the difference between minimum capacity C_{min} and maximum capacity C_{max}.

[0077] FIG. **12** illustrates a fourth embodiment of an electrostatically energy harvesting leadless capsule, wherein deformable element **42** is made of a flexible membrane **66**, fixed to housing **40** of the leadless capsule at its periphery and bearing in its center the part **52** for connection to movable electrode **50**.

[0078] FIG. **13** illustrates a fifth embodiment of an electrostatically energy harvesting leadless capsule, wherein deformable element **42** is made of a rigid movable element **44** extending from one edge to the other of housing **40**, connected to housing **40** by an elastic element **46** in the form of bellows instead of peripheral ripples **48** as illustrated in the embodiments of FIGS. **10** and **11**. This configuration advantageously allows in particular increasing both the travel of movable member **44**, and therefore that of the movable electrode, and the surface of rigid movable member **44** over which the external pressure is applied, with correlative increase of the force exerted at the center of this element.

[0079] FIG. **14** shows an improvement of the present invention, which is equally applicable to the various embodiments described above. This embodiment is configured to overcome one of the problems of harvesting of the forces exerted by changes in blood pressure, which is the change in atmospheric pressure. Indeed, the inside of the leadless capsule is sealed and therefore strictly at constant pressure (adjusted at the factory during manufacture). If the atmospheric pressure varies, the equilibrium at rest of the deformable element is offset relative to the nominal position at rest.

[0080] The proposed solution of the embodiment illustrated in FIG. **14** is to replace the rigid coupling between deformable element **42** and the movable electrode by a coupling incorporating a mechanical high-pass filter **68** interposed between the deformable element submitted to the external pressure and the electrostatic movable structure. This filter, for example, includes a piston **70** having a rod **52** connected to the movable electrode, with piston **70** moving in a fluid **72** such as air or other gas enclosed in a sealed enclosure **74**. In this way, the slow movements of deformable member **42** due to changes in atmospheric pressure are not transferred to the suspended movable electrode, the fluid being able to flow from either side of piston **70** through, by example, microstructured holes, or by a calibrated clearance **76**, so as to restore the pressure equilibrium. However, during rapid changes in the systole-diastole cardiac cycle, these pressure changes are fully transmitted to the suspended electrode, which can fully play the role assigned to it.

[0081] FIG. **15** illustrates an embodiment in the monolithic form of the structure combs/counter-combs produced by conventional photolithography techniques. Indeed, one of the difficulties of designing interdigitated structures of combs and counter-combs is to obtain a dielectric gap as small as possible, to maximize the capacity, while maintaining sufficient tolerance to prevent the combs to come in contact, to avoid they are unstable under the influence of the implemented electrostatic forces if the transverse stiffness of the fingers is too low, and that a breakdown between the electrodes happens if the electric field is too intense.

[0082] The device presented in the various embodiments described above (which are not in themselves limited), with a variable overlap out of plane, advantageously allows realization by conventional, in themselves known, microfabrication to manufacture electrostatic comb devices.

[0083] The combs **50** and counter-combs **54** can thus be simultaneously manufactured on a single slice of a typical substrate of silicon, heavily doped to be conductive. The separation of the combs to form the dielectric gap can be realized by deep etching of silicon using a technique such as

DRIE (Deep Reactive Ion Etching), allowing for example to obtain gaps of less than 10 microns on a slice thickness of the order of 300 to 500 microns. With gaps as low as 10 μm, for the gap between the combs remains constant and to avoid that the latter do not come to contact, alignment and assembly of two independent structures of combs is difficult. To overcome this difficulty, the structure can be performed on a slice of SOI (Silicon On Insulator) the substrate of which is structured so as to form, as shown in FIG. **15**, the combs and counter-combs **50**, **54** and their common supporting elements **60**, **64**, and wherein the upper layer (active) of the slice is structured so as to form very broad and thin springs **78** between each of the supports **64** of the movable structure and the peripheral ring **80** connected to the body **40** of the capsule.

[0084] These springs, because of their configuration, present an important rigidity in the plane containing the suspended movable structure of the combs **50**, and greatly limit the transverse displacements, typically at less than 1 μm. These elements ensure therefore, in addition a function of elastic support in the axial direction, a guiding and centering function in the transverse plane, thus guaranteeing a substantially constant dielectric gap. Because of the very small thickness of the springs **78**, they are very flexible in the vertical direction (axial), which therefore allows deformable member **42** of the leadless capsule and the suspended electrode constituted of combs **50** to axially move without difficulty and without adding significant stiffness.

[0085] FIGS. **16** and **17** illustrate two alternative embodiments of the capacitor structure, adapted to the use of reinforcement electret armatures having an electret film **57**, as described in the aforementioned articles of Peano & al. and Sakane & al. In this case, the electrodes are advantageously configured with overlap in the plane (FIG. **16**) or with a variable dielectric gap (FIG. **17**). The rest of the structure of the transducer is identical to what has been described, according to various embodiments illustrated and described with reference to FIGS. **5** and **10-14**.

[0086] One skilled in the art will appreciate the present invention may be practiced by other than the embodiments described herein, which are provided for purposed of illustration and not of limitation.

What is claimed is:

1. An autonomous intracorporeal leadless capsule, comprising:

a circuit;

an energy harvesting device with at least one movable surface for powering the circuit;

a capsule body having a deformable element directly exposed to an environment exterior of the capsule body, the circuit and the energy harvesting device within the capsule body; and

a mechanical high-pass filter positioned within the capsule body, wherein the mechanical high-pass filter comprises a piston having a rod, the rod extending from the piston out of a chamber and coupling to the at least one movable surface of the energy harvesting device.

2. The capsule of claim **1**, wherein the mechanical high-pass filter facilitates movement of the piston during high frequency displacements of the deformable element such that the movement of the piston is transferred to the at least one movable surface.

3. The capsule of claim **1**, wherein the mechanical high-pass filter prevents the movement of the piston during low frequency displacements of the deformable element such that the piston does not move.

4. The capsule of claim **1**, wherein the chamber is fixed to and movable with the deformable element with respect to at least one of the capsule body and the piston.

5. The capsule of claim **1**, wherein the chamber is filled with a fluid, the piston separating the chamber into a first volume and a second volume.

6. The capsule of claim **5**, wherein the piston and an inner surface of the chamber are separated by a calibrated clearance.

7. The capsule of claim **6**, wherein the calibrated clearance provides a passageway for the fluid to flow between the first volume and the second volume.

8. The capsule of claim **6**, wherein the calibrated clearance is sized to restore a pressure equilibrium within the chamber such that low frequency displacements of the deformable element are not transferred to the at least one movable surface.

9. A method for powering an autonomous intracorporeal leadless capsule, comprising:

receiving a low frequency pressure variation at an external surface of a deformable member on the capsule, the deformable member displacing in response to the low frequency pressure variation;

using a high pass mechanical filter to prevent displacement of a movable member of an energy harvesting device within the capsule responsive to the displacement of the deformable member due to the low frequency pressure variation;

receiving a high frequency pressure variation at the external surface of the deformable member on the capsule, the deformable member displacing in response to the high frequency pressure variation;

using the high pass mechanical filter to facilitate the displacement of the movable member of the energy harvesting device responsive to the displacement of the deformable member due to the high frequency pressure variation; and

generating energy with the energy harvesting device responsive to the displacement the movable member of the energy harvesting device.

10. The method of claim **9**, wherein the high pass mechanical filter comprises a piston coupled to the movable member of the energy harvesting device.

11. The method of claim **10**, wherein the displacement of the deformable member due to the high frequency pressure variation causes a displacement of the piston, causing the movable member of the energy harvesting device to displace.

12. The method of claim **10**, wherein the piston is enclosed within a fluid-filled chamber that is movable with the deformable member.

13. The method of claim **12**, wherein the piston and an inner surface of the fluid-filled chamber are separated by a calibrated clearance.

14. The method of claim **13**, wherein the calibrated clearance provides a passageway for a fluid to flow between a first volume and a second volume of the fluid-filled chamber.

15. The method of claim **13**, wherein the calibrated clearance is sized to restore a pressure equilibrium within the fluid-filled chamber such that the low frequency pressure variation does not displace the piston.

16. An autonomous intracorporeal leadless capsule, comprising:

a circuit;

an energy harvesting device including a capacitor configured to facilitate powering the circuit, the capacitor comprising opposing capacitor electrodes separated by a dielectric gap;

a capsule body having a deformable element directly exposed to an environment exterior of the capsule body, the circuit and the energy harvesting device within the capsule body; and

a mechanical high-pass filter positioned within the capsule body, wherein the mechanical high-pass filter comprises a piston having a rod, the rod extending from the piston out of a fluid-filled chamber and coupling to one of the opposing capacitor electrodes of the capacitor.

17. The capsule of claim **16**, wherein the opposing capacitor electrodes are movably suspended relative to the capsule body such that relative movement of the opposing capacitor electrodes generates power for powering the circuit.

18. The capsule of claim **16**, wherein the mechanical high-pass filter is configured to mechanically couple the deformable element and the opposing capacitor electrodes during high frequency displacements of the deformable element to generate power for powering the circuit.

19. The capsule of claim **16**, wherein the mechanical high-pass filter is configured to mechanically decouple the deformable element and the opposing capacitor electrodes during low frequency displacements of the deformable element.

20. The capsule of claim **16**, wherein the piston and an inner surface of the fluid-filled chamber are separated by a calibrated clearance, wherein the calibrated clearance is sized to restore a pressure equilibrium between a first volume and a second volume within the fluid-filled chamber such that low frequency displacements of the deformable element are not transferred to the one of the opposing capacitor electrodes of the capacitor by the piston.

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