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Energy harvesting element and energy harvesting device

Abstract

An energy harvesting element capable of efficiently generating power is provided. The energy harvesting element generates power by vibration, and includes a first electrode and a second electrode, a member having a third electrode electrically connected to the second electrode, and facing the first electrode, and a fourth electrode relatively fixed to the third electrode without being electrically connected to the third electrode, and electrically connected to the first electrode and facing the second electrode, the member being provided between the first electrode and the second electrode, and an electret provided in one of the first electrode and the third electrode, and one of the second electrode and the fourth electrode.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS

(1) This application is the United States national phase of International Application No. PCT/JP2021/037191 filed Oct. 7, 2021, and claims priority to Japanese Patent Application No. 2020-209682 filed Dec. 17, 2020, the disclosures of which are hereby incorporated by reference in their entireties.

BACKGROUND OF THE INVENTION

Field of the Invention

(2) The present invention relates to an energy harvesting element and an energy harvesting device.

Description of Related Art

(3) A vibration-driven energy harvesting element is known that includes two fixed electrodes and two movable electrodes, each having a comb-teeth portion (Patent Literature 1).

CITATION LIST

Patent Literature

(4) Patent Literature 1: Japanese Patent Laid-Open No. 2019-198161

SUMMARY OF INVENTION

Technical Problem

(5) In the vibration-driven energy harvesting element described in Patent Literature 1, power generation is performed in such a way that a change of the area of a portion where the fixed electrode and the movable electrodes face each other causes change of the charge induced by an electret, which changes potential difference between the fixed electrodes and the movable electrodes to generate an electromotive force. Conventionally, it has been desired to efficiently generate power.

Solution to Problem

(6) According to a first aspect of the present invention, an energy harvesting element generates power by vibration, and includes a first electrode and a second electrode, a member having a third electrode electrically connected to the second electrode, and facing the first electrode, and a fourth electrode relatively fixed to the third electrode without being electrically connected to the third electrode, and electrically connected to the first electrode and facing the second electrode, the member being provided between the first electrode and the second electrode, and an electret provided in one of the first electrode and the third electrode, and one of the second electrode and the fourth electrode.

(7) According to a second aspect of the present invention, an energy harvesting device includes the energy harvesting element according to the first aspect, and a rectifier having an electrode electrically connected to the first electrode and the fourth electrode, and an electrode electrically connected to the second electrode and the third electrode.

(8) According to a third aspect of the present invention, an energy harvesting element generates power by vibration, and includes a first electrode and a second electrode electrically connected to the first electrode, a member having a third electrode facing the first electrode, and a fourth electrode relatively fixed to the third electrode, and electrically connected to the third electrode and facing the second electrode, the member being provided between the first electrode and the second electrode, and an electret provided in one of the first electrode and the third electrode, and one of the second electrode and the fourth electrode.

(9) According to a fourth aspect of the present invention, an energy harvesting device includes the energy harvesting element according to the third aspect, and a rectifier having an electrode electrically connected to the first electrode and the second electrode, and an electrode electrically connected to the third electrode and the fourth electrode.

Advantageous Effect of Invention

(10) According to the present invention, power can be efficiently generated.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

(1) FIG. **1** is a diagram illustrating a configuration example of an energy harvesting device according to an embodiment.

(2) FIG. **2** is a diagram illustrating a configuration example of an energy harvesting element according to the embodiment.

(3) FIG. **3**A is a diagram for describing an example of the operation of the energy harvesting device according to the embodiment.

(4) FIG. **3**B is a diagram for describing an example of the operation of the energy harvesting device according to the embodiment.

(5) FIG. **4** is a diagram for describing processing performed by the energy harvesting device according to the embodiment.

(6) FIG. **5** is a diagram illustrating a configuration example of an energy harvesting device according to a modification.

DESCRIPTION OF THE INVENTION

Embodiment

(7) With reference to the drawings, an energy harvesting device according to an embodiment will be described. FIG. **1** is a diagram illustrating a configuration example of the energy harvesting device according to the embodiment. An energy harvesting device (vibration-driven energy harvesting device) **1** includes an energy harvesting element **10**, a converter **20**, a first output part **25**, and a second output part **26**, and generates power by utilizing vibration. The energy harvesting device **1** is an electrostatic energy harvesting device, and can be utilized as the technology of harvesting the energy of vibration in an environment to obtain power (energy harvesting).

(8) FIG. **2** is a diagram illustrating a configuration example of an energy harvesting element according to the embodiment. The energy harvesting element (vibration-driven energy harvesting element) **10** includes a support frame (support member) **11**, a movable part **12**, and a holding part **18**. The vibration-driven energy harvesting element **10** uses, for example, a silicon substrate or an SOI (Silicon On Insulator) substrate as a base material, and is manufactured by utilizing the MEMS technology.

(9) The support frame (base) **11** includes an electrode **16***a* and an electrode **16***b*. It can be said that the electrode **16***a* and the electrode **16***b* are electrodes fixed to and held by the support frame **11**. The electrode **16***a* and the electrode **16***b* are arranged in an up-and-down direction (X-axis direction) of the paper with the movable unit **12** being therebetween. In the following description, the fixed electrode **16***a* and electrode **16***b* will be referred to as the first fixed electrode **16***a* and the second fixed electrode **16***b*, respectively. Note that, as illustrated by coordinate axes in FIG. **1** and FIG. **2**, it is assumed that the right direction of the paper, which is orthogonal to an X axis, is a Y-axis plus direction. In the other diagrams, a coordinate axis may be displayed so that the orientation of each diagram can be recognized on the basis of the coordinate axes in FIG. **1** and FIG. **2**.

(10) The movable part **12** includes an electrode **13***a*, an electrode **13***b*, and an insulating part **15**. The electrode **13***a* and the electrode **13***b* are fixed to each other via the insulating part **15**. The electrode **13***a* and the electrode **13***b* are supported by the insulating part **15** to be in a relatively fixed state. The insulating part **15** is an insulating layer formed by an insulating material. The electrode **13***a* and the electrode **13***b* are provided such that they are separated by the insulating part **15**, and can also be called the separated electrodes.

(11) The movable part **12** is configured such that the electrode **13***a*, the electrode **13***b*, and the insulating part **15** are movable in the X-axis direction within the support frame **11**. The electrode **13***a*, the electrode **13***b*, and the insulating part **15** are vibrated in unison, when vibration is added to the vibration-driven energy harvesting element **10**. In the following description, the electrode **13***a*

and the electrode **13***b* will be referred to as the first movable electrode **13***a* and the second movable electrode **13***b*, respectively. The first movable electrode **13***a* and the first fixed electrode **16***a* are arranged to face each other, and can move relative to each other. Additionally, the second movable electrode **13***b* and the second fixed electrode **16***b* are also arranged to face each other, and can move relative to each other.

(12) The first fixed electrode **16***a*, the second fixed electrode **16***b*, the first movable electrode **13***a*, and the second movable electrode **13***b* each includes a portion forming a comb-teeth shape (comb-teeth portion), and serves as a comb-teeth-like electrode. A comb-teeth portion **17***a* of the first fixed electrode **16***a* and the comb-teeth portion **14***a* of the first movable electrode **13***a* are formed to be engaged with each other. Additionally, a comb-teeth portion **17***b* of the second fixed electrode **16***b* and a comb-teeth portion **14***b* of the second movable electrode **13***b* are also formed to be engaged with each other. Note that the number and arrangement of comb teeth that are provided in the first fixed electrode **16***a*, the second fixed electrode **16***b*, the first movable electrode **13***a*, and the second movable electrode **13***b* are not limited to the example illustrated.

(13) An electret is formed in the vicinity of surfaces of the first fixed electrode **16***a* that face the first movable electrode **13***a*. An electret is also formed in the vicinity of surfaces of the second fixed electrode **16***b* that face the second movable electrode **13***b*. The electret having a fixed charge is provided in the comb-teeth portion **17***a* of the first fixed electrode **16***a*, and the comb-teeth portion **17***b* of the second fixed electrode **16***b*. For example, an oxide film having a negative fixed charge is formed as an electret film (layer) in each of the comb-teeth portion **17***a* and the comb-teeth portion **17***b*. Each of the first fixed electrode **16***a* and the second fixed electrode **16***b* serves as an electretized electrode, and is semi-permanently charged. Note that, as schematically indicated by the symbols "-" in the figure, each of the first fixed electrode **16***a* and the second fixed electrode **16***b* will generally be in a negatively charged state.

(14) A capacity (electrostatic capacitance) is formed between the first fixed electrode **16***a* and the first movable electrode **13***a*. Additionally, an electrostatic capacitance is also formed between the second fixed electrode **16***b* and the second movable electrode **13***b*. Note that an electret having positive charge may be provided in the first fixed electrode **16***a* and the second fixed electrode **16***b*. Additionally, an electret having positive charge or negative charge may be provided in the first movable electrode **13***a* and the second movable electrode **13***b*.

(15) The holding part **18** is configured to have elasticity, and holds (supports) the movable part **12**. The holding part **18** is formed to have flexibility by using, for example, the same material (for example, silicon) as the first fixed electrode **16***a*, the second fixed electrode **16***b*, the first movable electrode **13***a*, and the second movable electrode **13***b*. The movable part **12** is in a state where the movable part **12** is elastically supported by the holding part **18**, and can move (vibrate) in the X-axis direction. Note that the holding part **18** may be formed by using a metal material, or may be formed by using other materials having flexibility.

(16) The vibration-driven energy harvesting element **10** can be connected to a component (circuit) that operates with power supplied from the vibration-driven energy harvesting element **10**. A converter that converts alternating current generated by the vibration-driven energy harvesting element **10** into direct current, a power storage part (capacitor, battery, or the like), a transformer (step-down circuit, step-up circuit, or the like) that transforms a voltage, and the like can be connected to the vibration-driven energy harvesting element **10**. In the example illustrated in FIG. **1**, the vibration-driven energy harvesting element **10** is electrically connected to the converter **20**, the power storage part **30**, and the transformer **40**.

(17) When vibration is given to the vibration-driven energy harvesting element **10** from the outside, deflection (elastic deformation) occurs in the holding part **18**, the movable part **12** is vibrated in the X-axis direction, and displacement of the first movable electrode **13***a* and the second movable electrode **13***b* occurs. When the first movable electrode **13***a* and the second movable electrode **13***b* are vibrated with respect to the first fixed electrode **16***a* and the second fixed electrode **16***b*, the

positional relationship between the first movable electrode **13***a* and the first fixed electrode **16***a* is changed, and the positional relationship between the second movable electrode **13***b* and the second fixed electrode **16***b* is also changed. With the movement of the movable part **12** in the X direction, the comb-teeth portion **14***a* of the first movable electrode **13***a* moves away from and close to the comb-teeth portion **17***a* of the first fixed electrode **16***a* in the X direction. Additionally, the comb-teeth portion **14***b* of the second movable electrode **13***b* moves away from and close to the comb-teeth portion **17***b* of the second fixed electrode **16***b* in the X direction.

(18) When the position of the first movable electrode **13***a* is changed, the interval (distance) between the first movable electrode **13***a* and the first fixed electrode **16***a* is changed, and the area of a region in the comb-teeth portion **14***a* of the first movable electrode **13***a* that faces the comb-teeth portion **17***a* of the first fixed electrode **16***a* is changed. According to the change in this area, (the size of) the electrostatic capacitance by the first movable electrode **13***a* and the first fixed electrode **16***a* is changed, and the charge amount induced in the first movable electrode **13***a* by the electret of the first fixed electrode **16***a* is changed. In this case, charge transfer occurs between the first fixed electrode **16***a* and an external circuit electrically connected to the first fixed electrode **16***a*. The charge transfer occurs in a connecting part (wire, terminal, or the like) W**1** illustrated in FIG. **1** and FIG. **2**, and a current is generated between the first fixed electrode **16***a* and the external circuit.

(19) Additionally, when the position of the second movable electrode **13***b* is changed, the interval between the second movable electrode **13***b* and the second fixed electrode **16***b* is changed, and the area of a region in the comb-teeth portion **14***b* of the second movable electrode **13***b* that faces the comb-teeth portion **17***b* of the second fixed electrode **16***b* is changed. According to the change in this area, the electrostatic capacitance by the second movable electrode **13***b* and the second fixed electrode **16***b* is changed, and the charge amount induced in the second movable electrode **13***b* by the electret of the second fixed electrode **16***b* is changed. In this case, charge transfer occurs between the second fixed electrode **16***b* and the external circuits electrically connected to the second fixed electrode **16***b*. The charge transfer occurs in a connecting portions (wire, terminal, or the like) W**2** illustrated in FIG. **1** and FIG. **2**, and a current is generated between the second fixed electrode **16***b* and the external circuit.

(20) The electrostatic capacitance between the first movable electrode **13***a* and the first fixed electrode **16***a* and the electrostatic capacitance between the second movable electrode **13***b* and the second fixed electrode **16***b* are changed in opposite phases. When the electrostatic capacitance between the first movable electrode **13***a* and the first fixed electrode **16***a* is varied, alternating current flows between the first fixed electrode **16***a* and the external circuit, and power is generated. Additionally, when the electrostatic capacitance between the second movable electrode **13***b* and the second fixed electrode **16***b* is varied, an alternating current flows between the second fixed electrode **16***b* and the external circuit, and power is generated.

(21) In this manner, in the energy harvesting device **1** according to the present embodiment, alternating current power can be generated by utilizing the change in the electrostatic capacitance that is caused due to vibration. Since the vibration-driven energy harvesting element **10** generates power between the first movable electrode **13***a* and the first fixed electrode **16***a*, and between the second movable electrode **13***b* and the second fixed electrode **16***b*, the amount of power generated can be increased. It becomes possible to efficiently convert vibrational energy into electric energy, and power generation efficiency can be improved.

(22) The converter **20** illustrated in FIG. **1** is configured to include two rectifiers (rectifier elements) **21**, and includes a function of converting alternating current into direct current. The converter **20** is a rectifier circuit that converts alternating current into direct current. Each of the two rectifiers **21** (a first rectifier **21***a*, a second rectifier **21***b*) is composed of a diode. The converter **20** is provided between the first output part **25** and the second output part **26**, and is electrically connected to the vibration-driven energy harvesting element **10**. The converter **20** converts alternating current (voltage) from the vibration-driven energy harvesting element **10** into direct

current. Note that the rectifier **21** may be composed by using a MOS transistor, or may be composed by using a bipolar transistor.

(23) The first output part **25** and the second output part **26** are parts (wires, terminals, or the like) to which the voltage (current) obtained by power generation by the vibration-driven energy harvesting element **10** is output. Power is supplied to the outside (the power storage part **30** and the transformer **40** in FIG. **1**) of the energy harvesting device **1** via the first output part **25** and the 2nd output part **26**. Note that, as illustrated in FIG. **1**, the second output part **26** and the wire W**2** are connected to an earthing wire (ground wire). The potential of the second output part **26** and the wire W**2** serves as a reference potential (earth potential) for the potential of each of the first output part **25** and the wire W**1**.

(24) The power storage part **30** is provided between the first output part **25** and the second output part **26**, and is supplied with power generated by the vibration-driven energy harvesting element **10**. The power storage part **30** is charged with power generated by the vibration-driven energy harvesting element **10**, and stores (accumulates) the power. In the example illustrated in FIG. **1**, the power storage part **30** is configured to include a capacitor C. An end of the capacitor C is connected to the first output part **25**, and the potential obtained by power generation is given to the end of the capacitor C. The other end of the capacitor C is connected to the second output part **26** and the wire W**2**, and the reference potential is given to the other end of the capacitor C. The power storage parts **30** is also a smoothing part that smoothen the voltage output by the vibration-driven energy harvesting element **10**. Note that the energy harvesting device **1** may be configured to include the power storage part **30**.

(25) The transformer **40** transforms and outputs the voltage that is input via the first output part **25** and the second output part **26**. The transformer (transforming circuit) **40** is a component used in combination with the vibration-driven energy harvesting element **10** during actual use, and operates as a load during actual use. The transformer **40** is, for example, a step-down circuit, and is composed of a DC-DC converter, or the like. The step-down circuit can output the voltage obtained by stepping down the voltage of the capacitor C. The component used as the transformer **40** is selected in consideration of the magnitude of the voltage and current that are output from the vibration-driven energy harvesting element **10**, and the like. Note that the energy harvesting device **1** may be configured to include the transformer **40**.

(26) In the example illustrated in FIG. **1**, the first rectifier **21***a* is composed by using a diode D**1**. An anode (terminal), which is one electrode of the diode D**1**, is electrically connected to the first fixed electrode **16***a* and the second movable electrode **13***b* of the vibration-driven energy harvesting element **10**. The first fixed electrode **16***a* and the second movable electrode **13***b* are both electrically connected to the wire W**1**, and are electrically connected to each other. Additionally, the anode of the diode D**1** is also electrically connected to the second rectifier **21***b*.

(27) A cathode (terminal), which is the other electrode of the diode D**1**, is electrically connected to the second fixed electrode **16***b* and the first movable electrode **13***a* of the vibration-driven energy harvesting element **10**. The second fixed electrode **16***b* and the first movable electrode **13***a* are both electrically connected to the wire W**2**, and are electrically connected to each other. Additionally, the cathode of the diode D**1** is connected to the other end of the capacitor C and the transformer **40** via the second output part **26**. The potential of the cathode of the diode D**1** is the earth potential.

(28) The second rectifier **21***b* is composed by using a diode D**2**. The cathode of the diode D**2** is electrically connected to the first fixed electrode **16***a* and the second movable electrode **13***b* of the vibration-driven energy harvesting element **10**. Additionally, the cathode of the diode D**2** is electrically connected to the first rectifier **21***a*. The anode of the diode D**2** is connected to the end of the capacitor C and the transformer **40** via the first output part **25**.

(29) In this manner, the energy harvesting device **1** according to the present embodiment includes the first movable electrode **13***a* and the second movable electrode **13***b* that are electrically separated from each other. The first fixed electrode **16***a* and the second movable electrode **13***b* are electrically

connected to each other, and the second fixed electrode **16***b* and the first movable electrode **13***a* are electrically connected to each other. A first pair (group) of the first fixed electrode **16***a* and the first movable electrode **13***a*, and a second pair of the second fixed electrode **16***b* and the second movable electrode **13***b* are in a state where the first pair and the second pair are connected in parallel.
(30) FIG. **3**A and FIG. **3**B are a diagram for describing an example of the operation of the energy harvesting device according to the embodiment. FIG. **3**A and FIG. **3**B schematically illustrate the current generated in the energy harvesting device **1**, when the movable part **12** is vibrated with respect to the first fixed electrode **16***a* and the second fixed electrode **16***b* in the X direction. FIG. **3**A illustrates a case where the movable part **12** is moved in a +X direction, and FIG. **3**B illustrates a case where the movable part **12** is moved in a −X direction.
(31) In the state illustrated in FIG. **3**A, with the movement of the movable part **12** in the +X direction, the area of the part where the comb-teeth portion **14***a* of the first movable electrode **13***a* and the comb-teeth portion **17***a* of the first fixed electrode **16***a* face each other is increased. Additionally, the area of the part where the comb-teeth portion **14***b* of the second movable electrode **13***b* and the comb-teeth portion **17***b* of the second fixed electrode **16***b* face each other is decreased. Therefore, the electrostatic capacitance between the first movable electrode **13***a* and the first fixed electrode **16***a* is increased, and the electrostatic capacitance between the second movable electrode **13***b* and the second fixed electrode **16***b* is decreased.
(32) Since the electrostatic capacitance between the first movable electrode **13***a* and the first fixed electrode **16***a* is increased, the amount of positive charge induced in the first movable electrode **13***a* by the electret of the first fixed electrode **16***a* is increased. Additionally, since the electrostatic capacitance between the second movable electrode **13***b* and the second fixed electrode **16***b* is decreased, the amount of positive charge induced in the second movable electrode **13***b* by the electret of the second fixed electrode **16***b* is decreased. At this time, negative charge (electrons) tries to move from the second fixed electrode **16***b* and the first movable electrode **13***a* toward the first fixed electrode **16***a* and the second movable electrode **13***b* via the wire W**1** and the wire W**2**, and the diode D**1** of the first rectifier **21***a* is in an ON state (forward bias state). The diode D**2** of the second rectifier **21***b* is in an OFF state (reverse bias state). When the first rectifier **21***a* is in the ON state, current flows as indicated by white arrows illustrated in FIG. **3**A.
(33) On the other hand, in the state illustrated in FIG. **3**B, with the movement of the movable part **12** in the −X direction, the area of the part where the comb-teeth portion **14***a* of the first movable electrode **13***a* and the comb-teeth portion **17***a* of the first fixed electrode **16***a* face each other is decreased, and the area of the part where the comb-teeth portion **14***b* of the second movable electrode **13***b* and the comb-teeth portion **17***b* of the second fixed electrode **16***b* face each other is increased. Therefore, the electrostatic capacitance between the first movable electrode **13***a* and the first fixed electrode **16***a* is decreased, and the electrostatic capacitance between the second movable electrode **13***b* and the second fixed electrode **16***b* is increased.
(34) Since the electrostatic capacitance between the first movable electrode **13***a* and the first fixed electrode **16***a* is decreased, the amount of positive charge induced in the first movable electrode **13***a* is decreased. Additionally, since the electrostatic capacitance between the second movable electrode **13***b* and the second fixed electrode **16***b* is increased, the amount of positive charge induced in the second movable electrode **13***b* is increased. At this time, negative charge tries to move from the first fixed electrode **16***a* and the second movable electrode **13***b* toward the side of the end of the capacitor C and the transformer **40**, which are connected to the first output part **25**, via the wire W**1**, and the second rectifier **21***b* is in the ON state. Additionally, the movement of negative charge occurs from the side of the other end of the capacitor C and the transformer **40**, which are connected to the second output part **26**, toward the second fixed electrode **16***b* and the first movable electrode **13***a* via the wire W**2**. The first rectifier **21***a* is in the OFF state.
(35) In this case of FIG. **3**B, current flows as indicated by white arrows in the figure. The current

according to the change in the electrostatic capacitance between the first movable electrode **13***a* and the first fixed electrode **16***a*, and the current according to change in the electrostatic capacitance between the second movable electrode **13***b* and the second fixed electrode **16***b* flow between the first output part **25** and the second output part **26**. The current obtained by combining the current obtained by power generation by the first pair of the first fixed electrode **16***a* and the first movable electrode **13***a*, and the current obtained by power generation by the second pair of the second fixed electrode **16***b* and the second movable electrode **13***b* will be output.
(36) In this manner, the energy harvesting device **1** according to the present embodiment outputs the current and voltage obtained by power generation by the two electrode pairs that are connected in parallel. Therefore, in the present embodiment, compared with a case where the first movable electrode **13***a* and the second movable electrode **13***b* are not electrically separated, it becomes possible to supply current of substantially twice the magnitude to the transformer **40**. Additionally, compared with a case where the first pair and the second pair are connected in series, it becomes possible to supply the voltage of substantially half the magnitude to the transformer **40**.
(37) When the voltage that is output from the vibration-driven energy harvesting element **10** is excessively high, a high voltage component is required as the subsequent transformer **40**, making the selection of components difficult. Additionally, there is a possibility that components become expensive, and the manufacturing cost of the energy harvesting device **1** is increased. On the other hand, in the present embodiment, it is possible to reduce the voltage that is output from the vibration-driven energy harvesting element **10**, and to reduce the voltage that is input to a subsequent circuit as described above. Therefore, it becomes possible to avoid that the selection of components to be used in the subsequent circuit becomes difficult. Additionally, it is possible to prevent an increase in the manufacturing cost of the energy harvesting device **1**.
(38) FIG. **4** is a diagram for describing processing performed by the energy harvesting device according to the embodiment. FIG. **4** illustrates an amplitude x of the movable part **12** (FIG. **4**(*a*)), and a voltage Vo of the first output part **25** (FIG. **4**(*b*)) on the same time axis. In FIG. **4**(*a*), a vertical axis represents the amplitude (amount of movement) of the movable part **12** in the X-axis direction. In FIG. **4**(*b*), the vertical axis represents the magnitude of voltage. The voltage Vo is the voltage applied to the end of the capacitor C and the transformer **40** via the first output part **25**.
(39) As described above by using FIG. **3**A and FIG. **3**B, in the energy harvesting device **1**, alternating current is generated that changes the direction of current between a case where the amplitude x of the movable part **12** has a positive value, that is, a case where the movable part **12** is moved in the +X direction, and a case where the amplitude x of the movable part **12** has a negative value, that is, the movable part **12** is moved in the −X direction. When the movable part **12** is moved in the +X direction, the diode D**1** is in the ON state, and the diode D**2** is in the OFF state. When the movable part **12** is moved in the −X direction, the diode D**1** is in the OFF state, and the diode D**2** is in the ON state.
(40) In a period from a time t**1** to a time t**2** illustrated in FIG. **4**(*a*) and FIG. **4**(*b*), with the movement of the movable part **12** in the +X direction, the diode D**1** is in the ON state, and the diode D**2** is in the OFF state. In this case, current flows from the first fixed electrode **16***a* and second movable electrode **13***b* side to the second fixed electrode **16***b* and first movable electrode **13***a* side via the diode D**1**.
(41) In a period from the time t**2** to a time t**3**, with the movement of the movable part **12** in the −X direction, the diode D**2** is in the ON state, and the diode D**1** is in the OFF state. In this case, current flows from the second fixed electrode **16***b* and first movable electrode **13***a* side to the first fixed electrode **16***a* and second movable electrode **13***b* side via the diode D**2**, the first output part **25**, and the second output part **26**. The current obtained by combining the current obtained by power generation by the first movable electrode **13***a* and the first fixed electrode **16***a*, and the current obtained by power generation by the second movable electrode **13***b* and the second fixed electrode **16***b* is output to the power storage part **30** and the transformer **40**. Accordingly, the capacitor C is

charged, and the value (level) of the voltage Vo is increased as indicated by a bold line in FIG. **4**(*b*). Note that, in the example illustrated in FIG. **4**, the voltage Vo has a negative value.

(42) In a period from the time t**3** to a time t**4**, similar to the case of the period from the time t**1** to the time t**2**, current flows in the energy harvesting device **1** according to the movement of the movable part **12** in the +X direction. In this case, the diode D**2** is in the OFF state as described above. Therefore, the charge accumulated in the capacitor C is retained, and deterioration of the voltage Vo can be suppressed.

(43) In a period from the time t**4** to a time t**5**, similar to the case of the period from the time t**2** to the time t**3**, current flows in the energy harvesting device **1** according to the movement of the movable part **12** in the −X direction. In this case, the capacitor C is charged, and the value of the voltage Vo is increased. The voltage Vo of the capacitor C charged by power generation by the vibration-driven energy harvesting element **10** is supplied to the transformer **40**.

(44) In this manner, the energy harvesting device **1** according to the present embodiment generates power by the first pair of the first fixed electrode **16***a* and the first movable electrode **13***a*, and the second pair of the second fixed electrode **16***b* and the second movable electrode **13***b*. Therefore, the energy harvesting device **1** can efficiently generate power. Additionally, since power is generated by the two electrode pairs that are electrically connected in parallel, it is possible to reduce the voltage supplied to the outside of the energy harvesting device **1**, and to increase the current supplied to the outside of the energy harvesting device **1**. The ratio between the voltage and the current that are output from the vibration-driven energy harvesting element **10**, that is, impedance (output impedance) can be reduced. Therefore, it becomes possible to avoid that the selection of a component to be used as the transformer **40** becomes difficult.

(45) Additionally, in the energy harvesting device **1** according to the present embodiment, rectification is performed by the two diodes D**1** and D**2**. Therefore, compared with a case where rectification is performed by using a large number of diodes, the loss of power in the diodes can be suppressed, and the power generation efficiency can be improved. Additionally, it is possible to prevent an increase in the manufacturing cost of the energy harvesting device **1**.

(46) Note that, although the configuration example of the converter **20** has been described in the above, the configuration example is merely an example, and the configuration of the converter (rectifier circuit) **20** is not limited to the above-described example. The configuration of the converter **20** can be appropriately changed, and may be configured to include, for example, three or more diodes. A rectifier circuit in which four diodes are arranged in a bridge configuration may be used as the converter **20**.

(47) According to the above-described embodiment, the following effects can be obtained. (1) An energy harvesting element (vibration-driven energy harvesting element **10**) generates power by vibration, and includes a first electrode (first fixed electrode **16***a*) and a second electrode (second fixed electrode **16***b*), a member (movable part **12**) having a third electrode (first movable electrode **13***a*) electrically connected to the second electrode, and facing the first electrode, and a fourth electrode (second movable electrode **13***b*) relatively fixed to the third electrode without being electrically connected to the third electrode, and electrically connected to the first electrode and facing the second electrode, the member being provided between the first electrode and the second electrode, and an electret provided in one of the first electrode and the third electrode, and one of the second electrode and the fourth electrode. Since being configured as described above, the vibration-driven energy harvesting element **10** according to the present embodiment can efficiently generate power. Additionally, since power is generated by the two electrode pairs that are connected in parallel, the output impedance can be reduced. Accordingly, it is possible to avoid that the selection of components to be connected to the vibration-driven energy harvesting element **10** becomes difficult.

(48) (2) The energy harvesting device **1** includes the energy harvesting element (vibration-driven energy harvesting element **10**), and the converter **20** that converts alternating current generated by

the energy harvesting element to direct current. The converter **20** includes the first rectifier **21***a* having the electrode (anode) electrically connected to the first electrode and the fourth electrode, and the electrode (cathode) electrically connected to the second electrode and the third electrode, and the second rectifier **21***b* having the electrode (cathode) electrically connected to the first electrode and the fourth electrode, and the electrode (anode) electrically connected to the output part (first output part **25**). Since the energy harvesting device **1** according to the present embodiment performs rectification by the two diodes, compared with a case where rectification is performed by a large number of diodes, the loss of power in the energy harvesting device **1** can be suppressed, and the power generation efficiency can be improved. Additionally, it is possible to prevent an increase in the manufacturing cost of the energy harvesting device **1**.
(49) With reference to the drawings, a modification will be described below. Note that, in the figures, the same reference numbers are given to the parts that are identical or corresponding to the parts in the above-described embodiment, and the differences from the above-described embodiment will be mainly described.
(50) FIG. **5** is a diagram illustrating a configuration example of an energy harvesting device according to a modification. In the example illustrated in FIG. **5**, the anode of the diode D**1** of the converter **20** is electrically connected to the first fixed electrode **16***a* and the second fixed electrode **16***b* of the vibration-driven energy harvesting element **10**. The first fixed electrode **16***a* and the second fixed electrode **16***b* are both electrically connected to the wire W**1**, and are electrically connected to each other. The cathode of the diode D**1** is electrically connected to the first movable electrode **13***a* and the second movable electrode **13***b* of the vibration-driven energy harvesting element **10**. The first movable electrode **13***a* and the second movable electrode **13***b* are both electrically connected to the wire W**2**, and are electrically connected to each other. The cathode of the diode D**2** of the converter **20** is electrically connected to the first fixed electrode **16***a*, the second fixed electrode **16***b*, and the anode of the diode D**1**.
(51) Additionally, in the present modification, each of the first fixed electrode **16***a* and the second movable electrode **13***b* is provided with an electret having negative charge, and serves as an electretized electrode. Note that an electret having positive charge may be provided in the first fixed electrode **16***a* and the second movable electrode **13***b*. An electret having positive charge or negative charge may be provided in the second fixed electrode **16***b* and the first movable electrode **13***a*.
(52) Also in the present modification, the first pair of the first fixed electrode **16***a* and the first movable electrode **13***a*, and the second pair of the second fixed electrode **16***b* and the second movable electrode **13***b* are in the state where the first pair and the second pair are connected in parallel. The energy harvesting device **1** can generate power by the two electrode pairs that are electrically connected in parallel, and the voltage supplied to the outside of the energy harvesting device **1** can be reduced. Therefore, the output impedance can be reduced, and it is possible to prevent that the selection of components to be connected to the vibration-driven energy harvesting element **10** become difficult.
(53) Although various embodiments and modifications have been described in the above, the present invention is not limited to these contents. The other aspects that can be considered within the scope of the technical idea of the present invention are also included in the scope of the present invention.
REFERENCE SIGNS LIST
(54) **1** energy harvesting device **10** energy harvesting element **12** movable part **13***a* first movable electrode **13***b* second movable electrode **15** insulating part **16***a* first fixed electrode **16***b* second fixed electrode **20** converter **21***a* first rectifier **21***b* second rectifier **25** first output part **26** second output part **30** power storage part **40** transformer

Claims

1. An energy harvesting element that generates power by vibration, the energy harvesting element comprising: a first electrode and a second electrode; a member having a third electrode electrically connected to the second electrode, and facing the first electrode, and a fourth electrode relatively fixed to the third electrode without being electrically connected to the third electrode, and electrically connected to the first electrode and facing the second electrode, the member being provided between the first electrode and the second electrode; and an electret provided in one of the first electrode and the third electrode, and one of the second electrode and the fourth electrode.
2. The energy harvesting element according to claim 1, wherein the fourth electrode is fixed to the third electrode via an insulating part.
3. The energy harvesting element according to claim 1, wherein the member is a movable part that is movable with respect to the first electrode and the second electrode.
4. The energy harvesting element according to claim 3, wherein the movable part is vibrated between the first electrode and the second electrode when vibration is given from an outside, and when the movable part is vibrated, power is generated by the first electrode and the third electrode, and power is generated by the second electrode and the fourth electrode.
5. An energy harvesting device, comprising: the energy harvesting element according to claim 1; and a rectifier having an electrode electrically connected to the first electrode and the fourth electrode, and an electrode electrically connected to the second electrode and the third electrode.
6. The energy harvesting device according to claim 5, wherein the rectifier rectifies alternating current generated by the first electrode and the third electrode, and the second electrode and the fourth electrode.
7. The energy harvesting device according to claim 6, wherein the rectifier is a diode.
8. An energy harvesting element that generates power by vibration, the energy harvesting element comprising: a first electrode and a second electrode electrically connected to the first electrode; a member having a third electrode facing the first electrode, and a fourth electrode relatively fixed to the third electrode, and electrically connected to the third electrode and facing the second electrode, the member being provided between the first electrode and the second electrode; and an electret provided in one of the first electrode and the third electrode, and one of the second electrode and the fourth electrode wherein the first electrode and the second electrode are both electrically connected to an external circuit via the same wire.
9. An energy harvesting device, comprising: the energy harvesting element according to claim 8; and a rectifier having an electrode electrically connected to the first electrode and the second electrode, and an electrode electrically connected to the third electrode and the fourth electrode.