

ELECTRON PUMPS

Cross-Reference To Related Application

This application claims the benefit of Singapore Patent Application No. 10201705653S,
5 entitled Electron Pumps and filed on July 10, 2017, which is expressly incorporated by
reference herein in its entirety.

Field of the Invention

This disclosure relates to an energy harvester and a method thereof. Particularly, this
10 disclosure relates to an energy harvester in which the charging process can be completed
in a very short time.

Summary of the Prior Art

Electric energy can be converted from mechanical energy using one of the following
15 principles: electromagnetic induction, electrostatic induction, triboelectric effect,
piezoelectric effect, etc. Most of electricity for daily life and industry is generated through
electromagnetic induction. In an electromagnetic generator, a coil rotates or vibrates in a
magnetic field to achieve a magnetic flux change and create a conduction current
according to Faraday's law. Electromagnetic generators are typically bulky. Although
20 several microelectromagnetic generators have been demonstrated using
microelectromechanical systems (MEMS), it is still very challenging to miniaturize them
down to a sub millimeter scale.

Electrostatic generators accumulate charges of opposite signs in two electrodes which
25 form a capacitor. Relative motion of the two electrodes by mechanical power leads to
charging or discharging of the capacitor through the external circuit, accomplishing the
power conversion. Electrostatic generators were invented much earlier than
electromagnetic generators. However, they have much lower power efficiencies than
electromagnetic generators due to very high internal resistance. Hence, electrostatic
30 generators have never had extensive applications as electromagnetic generators.

Triboelectric generators and piezoelectric generators have attracted a lot of attention due
to their small dimensions and multiple applications. A triboelectric generator contains two

electrodes whose electron affinities are largely different. One electrode must be an insulator while the other can be either a metal or an insulator. When the two electrodes are brought into contact, electrons could transfer from the low electron affinity electrode to the high electron affinity electrode so that one electrode surface is positively charged and the other is negatively charged. If the backsides of the insulating electrodes are coated with metal layers, charges can be induced to the metal layers through electrostatic induction when the two electrodes are separating, forming a transient current flowing through a closed external circuit with a load and converting the mechanical power that is used to separate the two electrodes into electric power that is dissipated onto the external circuit and the load.

Piezoelectric generators harvest mechanical energy when a force or stress is applied onto a piezoelectric material to cause the charge centers for the cations and anions separated, forming dipole moments across the piezoelectric material. If the two terminals of the material are electrically connected through a load, a current in the external circuit is induced. In short, when the piezoelectric material is subjected to a variable mechanical strain, it becomes electrically polarized at its two terminals, causing a displacement current across the material.

Unfortunately, the internal resistances of triboelectric generators and piezoelectric generators are very high, ranging from Mega ohm ($M\Omega$) up to Giga ohm ($G\Omega$). The high internal resistance is not favourable for electric generators. Furthermore, electrostatic generators, triboelectric generators and piezoelectric generators share a common characteristic in that only displacement current is generated internally and it is capacitively coupled to the external circuits. Under capacitive coupling, the power delivered to the load resistor is determined by the actual variation of the capacitance C between the two electrodes, internal impedance of the generator, the load resistance R and parasitic capacitance and resistance, etc. The actual variation of C is associated with the mechanical power source. R should match with the internal impedance. On one hand, a large C is desirable to accommodate more charges and reduce the capacitive reactance, but, on the other hand, a large C leads to a large time constant RC , or a slow charging process, affecting the power conversion efficiency.

Hence, those skilled in the art are striving to provide a more efficient and productive manner of harvesting energy for small scale electric generators.

Summary of the Invention

5 The above and other problems are solved and an advance in the state of the art is made by systems and methods provided by embodiments in accordance with the disclosure. The first advantage of embodiments of systems and methods in accordance with the disclosure is that systems and methods are able to harvest energy in a very short time compared to current devices. The second advantage of embodiments of systems and methods in
10 accordance with the disclosure is that systems and methods are able to harvest kinetic energy into electricity for small scale devices. Hence, this reduces the cost of operating devices as capacity of batteries (if still required) can be substantially reduced. This also reduces the energy footprint. The third advantage of embodiments of system and methods in accordance with the disclosure is that systems and methods make use of semiconductor
15 materials and metals that can be easily integrated into IC chips and other semiconductor devices.

A first aspect of the disclosure relates to an energy harvester. The energy harvester comprises a first electrode, a second electrode and a load. The first electrode comprises a
20 first semiconductor material. The second electrode comprises at least one of a second semiconductor material and a metal material. The load is electrically connected to the first and second electrodes. The load is between the first and second electrodes electrically connecting a first end of the first electrode and a first end of the second electrode. Relative movement of the first electrode and the second electrode causes the first and second
25 electrodes to be in contact with each other and subsequently apart from each other generating a current flow through the load. In more detail, relative movement of the first electrode and the second electrode causes a second end of the first electrode and a second end of the second electrode to be in contact with each other and subsequently apart from each other generating a current flow through the load.

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In an embodiment of the first aspect of the disclosure, the first semiconductor material is an n-type semiconductor material and the first end of the first electrode is coated with a low work function metal. Further, the second electrode comprises the second

semiconductor material. The second semiconductor material is a p-type semiconductor and the first end of the second electrode is coated with a high work function metal. In this embodiment, the first electrode further comprises a first passivation layer and the second electrode further comprises a second passivation layer. The first electrode is being
5 arranged such that the n-type semiconductor material is between the first passivation layer and the low work function metal, and the second electrode is being arranged such that the p-type semiconductor material is between the second passivation layer and the high work function metal.

10 In an embodiment of the first aspect of the disclosure, the first semiconductor material is an n-type semiconductor material and the first end of the first electrode is coated with a low work function metal. Further, the second electrode comprises the metal material. In this embodiment, the first electrode further comprises a passivation layer and the first electrode is being arranged such that the n-type semiconductor material is between the
15 passivation layer and the low work function metal.

In an embodiment of the first aspect of the disclosure, the first semiconductor material is a p-type semiconductor material and the first end of the first electrode is coated with a high work function metal. Further, the second electrode comprises the metal material. In this
20 embodiment, the first electrode further comprises a passivation layer and the first electrode is being arranged such that the p-type semiconductor material is between the passivation layer and the high work function metal.

In an embodiment of the first aspect of the disclosure, the first semiconductor material
25 comprises an n-type semiconductor material and a p-type semiconductor material. The first end of the first electrode is coated with a low work function metal. The first electrode is being arranged such that the n-type semiconductor material is between the p-type semiconductor material and the low work function metal. Further, the second electrode comprises the second semiconductor material and the metal material. The second
30 semiconductor material is an n-type semiconductor material and the metal material is a low work function metal coated onto the first end of the second electrode. In this embodiment, the first electrode further comprises a first passivation layer and the second electrode further comprises a second passivation layer. The first electrode is being

arranged such that the p-type semiconductor material is between the first passivation layer and the n-type semiconductor material, and the second electrode is being arranged such that the n-type semiconductor material is between the second passivation layer and the low work function metal.

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In an embodiment of the first aspect of the disclosure, the first semiconductor material comprises an n-type semiconductor material and a p-type semiconductor material. The first end of the first electrode is coated with a high work function metal. The first electrode is being arranged such that the p-type semiconductor material is between the n-type semiconductor material and the high work function metal. Further, the second electrode comprises the second semiconductor material and the metal material. The second semiconductor material is a p-type semiconductor material and the first end of the second electrode is coated with a high work function metal. In this embodiment, the first electrode further comprises a first passivation layer and the second electrode further comprises a second passivation layer. The first electrode is being arranged such that the n-type semiconductor material is between the first passivation layer and p-type semiconductor material and the second electrode is being arranged such that the p-type semiconductor material is between the second passivation layer and the high work function metal.

In an embodiment of the first aspect of the disclosure, the first semiconductor material comprises an n-type semiconductor material and a p-type semiconductor material and the second electrode comprises the metal material. The first end of the first electrode is coated with a low work function metal and the first electrode is being arranged such that the n-type semiconductor material is between the p-type semiconductor material and the low work function metal. The second electrode comprises the metal material which is a low work function metal. In this embodiment, the first electrode further comprises a passivation layer. The first electrode is being arranged such that the p-type semiconductor material is between the passivation layer and the n-type semiconductor material.

In an embodiment of the first aspect of the disclosure, the first semiconductor material comprises an n-type semiconductor material and a p-type semiconductor material and the first end of the first electrode is coated with a high work function metal. The first electrode is being arranged such that the p-type semiconductor material is between the n-type

semiconductor material and the high work function metal. The second electrode comprises the metal material which is a high work function metal. In this embodiment, the first electrode further comprises a passivation layer. The first electrode is being arranged such that the n-type semiconductor material is between the passivation layer and p-type semiconductor material.

In an embodiment of the first aspect of the disclosure, the first semiconductor material comprises an n-type semiconductor material and a p-type semiconductor material. The first end of the first electrode is coated with a low work function metal. The first electrode is being arranged such that the n-type semiconductor material is between the p-type semiconductor material and the low work function metal. Further, the second electrode comprises the second semiconductor material and the metal material. The second semiconductor material comprises a p-type semiconductor material and an n-type semiconductor material. The metal material is a high work function metal. The second electrode is being arranged such that the p-type semiconductor material is between the n-type semiconductor material and the high work function metal. In this embodiment, the first electrode further comprises a first passivation layer and the second electrode further comprises a second passivation layer. The first electrode is being arranged such that the p-type semiconductor material is between the first passivation layer and the n-type semiconductor material and the second electrode is being arranged such that the n-type semiconductor material is between the second passivation layer and the p-type semiconductor material.

A second aspect of the disclosure relates to a method of harvesting energy. The method comprises: providing a first electrode comprising a first semiconductor material; providing a second electrode comprising at least one of a second semiconductor material and a metal material; connecting the first end of a load to the first end of the first electrode and the second end of the load to the first end of the second electrode; and generating a current flow through the load in response to relative movement of the first electrode and the second electrode such that a second end of the first electrode and a second end of the second electrode are in contact with each other and subsequently apart from each other.

In an embodiment of the second aspect of the disclosure, the first semiconductor material is an n-type semiconductor material and the first end of the first electrode is coated with a low work function metal. Further, the second electrode comprises the second semiconductor material. The second semiconductor material is a p-type semiconductor and
5 the first end of the second electrode is coated with a high work function metal. In this embodiment, the first electrode further comprises a first passivation layer and the second electrode further comprises a second passivation layer. The first electrode is being arranged such that the n-type semiconductor material is between the first passivation layer and the low work function metal and the second electrode is being arranged such that the
10 p-type semiconductor material is between the second passivation layer and the high work function metal.

In an embodiment of the second aspect of the disclosure, the first semiconductor material is an n-type semiconductor material where the first end of the first electrode is coated with
15 a low work function metal. The second electrode comprises the metal material which is a low work function metal. In this embodiment, the first electrode further comprises a passivation layer. The first electrode is being arranged such that the n-type semiconductor material is between the passivation layer and the low work function metal.

20 In an embodiment of the second aspect of the disclosure, the first semiconductor material is a p-type semiconductor material and the first end of the first electrode is coated with a high work function metal. The second electrode comprises the metal material which is a low work function metal. In this embodiment, the first electrode may further comprise a passivation layer and the first electrode is being arranged such that the p-type
25 semiconductor material is between the passivation layer and the high work function metal.

In an embodiment of the second aspect of the disclosure, the first semiconductor material comprises an n-type semiconductor material and a p-type semiconductor material, and the first end of the first electrode is coated with a low work function metal. The first electrode
30 is being arranged such that the n-type semiconductor material is between the p-type semiconductor material and the low work function metal. Further, the second electrode comprises the second semiconductor material and the metal material. The second semiconductor material is an n-type semiconductor material and the metal material is a

low work function metal coated onto the first end of the second electrode. In this embodiment, the first electrode further comprises a first passivation layer and the second electrode further comprises a second passivation layer. The first electrode is being arranged such that the p-type semiconductor material is between the first passivation layer and the n-type semiconductor material and the second electrode is being arranged such that the n-type semiconductor material is between the second passivation layer and the low work function metal.

In an embodiment of the second aspect of the disclosure, the first semiconductor material comprises an n-type semiconductor material and a p-type semiconductor material, and the first end of the first electrode is coated with a high work function metal. The first electrode is being arranged such that the p-type semiconductor material is between the n-type semiconductor material and the high work function metal. Further, the second electrode comprises the second semiconductor material and the metal material. The second semiconductor material is a p-type semiconductor material and the metal material is a high work function metal coated onto the first end of the second electrode. In this embodiment, the first electrode further comprises a first passivation layer and the second electrode further comprises a second passivation layer. The first electrode is being arranged such that the n-type semiconductor material is between the first passivation layer and p-type semiconductor material and the second electrode is being arranged such that the p-type semiconductor material is between the second passivation layer and the high work function metal.

In an embodiment of the second aspect of the disclosure, the first semiconductor material comprises an n-type semiconductor material and a p-type semiconductor material. The first end of the first electrode is coated with a low work function metal and the first electrode is being arranged such that the n-type semiconductor material is between the p-type semiconductor material and the low work function metal. The second electrode comprises the metal material which is a low work function metal. In this embodiment, the first electrode further comprises a passivation layer and the first electrode is being arranged such that the p-type semiconductor material is between the passivation layer and the n-type semiconductor material.

In an embodiment of the second aspect of the disclosure, the first semiconductor material comprises an n-type semiconductor material and a p-type semiconductor material. The first end of the first electrode is coated with a high work function metal and the first electrode is being arranged such that the p-type semiconductor material is between the n-type semiconductor material and the high work function metal. The second electrode comprises the metal material which is a high work function metal. In this embodiment, the first electrode further comprises a passivation layer and is being arranged such that the n-type semiconductor material is between the passivation layer and p-type semiconductor material.

In an embodiment of the second aspect of the disclosure, the first semiconductor material comprises an n-type semiconductor material and a p-type semiconductor material. The first end of the first electrode is coated with a low work function metal. The first electrode is being arranged such that the n-type semiconductor material is between the p-type semiconductor material and the low work function metal. Further, the second electrode comprises the second semiconductor material and the metal material. The second semiconductor material comprises a p-type semiconductor material and an n-type semiconductor material. The metal material is a high work function metal and the second electrode is being arranged such that the p-type semiconductor material is between the n-type semiconductor material and the high work function metal. In this embodiment, the first electrode further comprises a first passivation layer and the second electrode further comprises a second passivation layer. The first electrode is being arranged such that the p-type semiconductor material is between the first passivation layer and the n-type semiconductor material and the second electrode is being arranged such that the n-type semiconductor material is between the second passivation layer and the p-type semiconductor material.

Brief Description of the Drawings

The above advantages and features in accordance with this invention are described in the following detailed description and are shown in the following drawings:

Figure 1A illustrates an energy band diagrams for a pair of p-type and n-type semiconductor electrodes in the insulated stage and the space charge distribution and the connected circuit;

Figure 1B illustrates the pair of p-type and n-type semiconductor electrodes in figure 1A when in the contacted stage;

Figure 1C illustrates the pair of p-type and n-type semiconductor electrodes in figure 1A when in the separating stage;

5 Figure 1D illustrates the pair of p-type and n-type semiconductor electrodes in figure 1A when in the separated stage;

Figure 2A illustrates space charge distributions and depletion regions in the p-type and n-type semiconductor electrodes in the contacted stage;

10 Figure 2B illustrates space charge distributions and depletion regions in the p-type and n-type semiconductor electrodes in the separating stage;

Figure 3 illustrates transient current and voltage generated by the p+-type Si and n-type Si electrode pair under $R=50\text{ M}\Omega$;

Figure 4 illustrates transient current, integrated charge and average peak power from p+-type Si & n-type Si electrode pair;

15 Figure 5 illustrates the transient current and voltage generated by an Au & n+-type Si electrode pair under $R=50\text{ M}\Omega$;

Figure 6 illustrates the transient current, integrated charge and average peak power from Au & n+-type Si electrode pair;

20 Figure 7 illustrates the influences of the electrode area for the p+-type Si and n-type Si electrode pair and the Au and n+-type Si electrode pair;

Figure 8 illustrates a first embodiment;

Figure 9 illustrates the first embodiment when in the contacted stage;

Figure 10 illustrates the first embodiment when in the separating stage;

Figure 11 illustrates the first embodiment when in the separated stage;

25 Figure 12 illustrates adding of passivation layer on the first embodiment;

Figure 13 illustrates a process for harvesting energy;

Figure 14 illustrates a second embodiment;

Figure 15 illustrates the second embodiment when in the contacted stage;

Figure 16 illustrates the second embodiment when in the separating stage;

30 Figure 17 illustrates the second embodiment when in the separated stage;

Figure 18 illustrates adding of passivation layer on the second embodiment;

Figure 19 illustrates an alternative of the second embodiment;

Figure 20 illustrates adding of passivation layer on the alternative second embodiment;

Figure 21 illustrates a third embodiment;

Figure 22 illustrates adding of passivation layer on the third embodiment;

5 Figure 23 illustrates an alternative of the third embodiment;

Figure 24 illustrates adding of passivation layer on the alternative third embodiment;

Figure 25 illustrates a fourth embodiment;

Figure 26 illustrates adding of passivation layer on the fourth embodiment;

10 Figure 27 illustrates an alternative of the fourth embodiment;

Figure 28 illustrates adding of passivation layer on the alternative fourth embodiment;

Figure 29 illustrates a fifth embodiment;

Figure 30 illustrates adding of passivation layer on the fifth embodiment;

15 Figure 31 illustrates a first application for use in the embodiments of this disclosure;

Figure 32 illustrates a second application for use in the embodiments of this disclosure;

20 Figure 33 illustrates a third application for use in the embodiments of this disclosure; and

Figure 34 illustrates a fourth application for use in the embodiments of this disclosure.

Detailed Description

25 This disclosure relates to an energy harvester and a method thereof. Particularly, this disclosure relates to an energy harvester in which the charging process can be completed in a very short time.

30 The energy harvesters according to this disclosure can be used as electric current generators, mechanical energy harvesters, mechanical-electric interfaces, sensors, etc. The structures and working principle of the devices are fundamentally different from those of well reported generators that could convert mechanical energy into electric energy.

In this disclosure, electric transient current is generated when the two electrodes are being separated. P-type semiconductors, n-type semiconductors and low and high work function metals in various combinations can be implemented as the electrode materials. Briefly, the energy harvester comprises a first electrode, a second electrode and a load. The first electrode comprises at least one of a first semiconductor material and a metal material and the second electrode comprises at least one of a second semiconductor material and a metal material. The load is provided between the first and second electrodes and is electrically connected to the first end of the first and second electrodes. Relative movement of the first electrode and second electrode causes the second end of the first and second electrodes to be in contact with each other and subsequently apart from each other generating a current flow through the load. The working principle of the energy harvester will first be described followed by the details of the two electrodes pairing.

For purposes of this disclosure, the semiconductors mean all types of semiconducting materials, including inorganic semiconductors and organic semiconductors, regardless of their dimensions and crystallinities. Inorganic semiconductors include silicon, III-V semiconductors, metal oxide semiconductors, etc. The semiconductors can be 0, 1 and 2 dimensional semiconducting nanomaterials, etc. Selection of low and high work function metals is determined by the semiconducting materials used. Silicon is used as an example for further discussion. The low work function metals mean the metals which have smaller work functions (while they are relatively stable in the ambient environment), typically less than 4.3 eV, such as Al, Ti, Ag, Pb, etc. The high work function metals mean the metals which have larger work functions, typically higher than 5.0 eV, such as Au, Pt, Ni, etc. The dielectric materials refer to SiO₂, Si₃N₄, Al₂O₃, HfO₂, etc. One skilled in the art will recognise that the list here is not meant to be exhaustive and other high and low function materials and dielectric material may be implemented without departing from the disclosure.

When the two electrodes are in contact, electrons can diffuse from the electrode with n-type semiconductors or low work function metals to the electrode with p-type semiconductors or high work function metals. When the electrodes are being separated, the transferred electrons flow back through the external connection with a load resistance R , causing a transient current opposite the electron flow. In short, in one cycle from the

“contacted stage”, “separating stage”, “separated stage” back to “contacted stage”, electrons move in a closed loop from one electrode, the external circuit and load and then back to the other electrode. The equivalent internal resistance of the energy harvesters could be smaller than the generators based on electrostatic induction, the triboelectric effect, the piezoelectric effect. Further, the charging process can be completed in a very short time, as it is not affected by RC .

Referring to Figures 1A-1D, first electrode 10 comprises a p -type semiconductor with a lower chemical potential (or a larger work function $q\phi_1$) and second electrode 20 comprises an n -type semiconductor with a higher chemical potential (or a smaller work function $q\phi_2$). The surfaces of the semiconductor electrodes are assumed to be ideal and no surface states exist. Thus, the energy band diagrams of the two electrodes before electrical connection can be shown above the two electrodes 10 and 20 in figure 1A. As shown in figure 1B, when the two electrodes 10 and 20 are brought in contact (i.e. contacted stage), electrons diffuse from second electrode 20 to first electrode 10 while holes diffuse from first electrode 10 to second electrode 20 due to the chemical potential difference, $V_B = \phi_1 - \phi_2$, leading to formation of a negative space charge (or depletion) region with the depletion width of W_p in the p -type semiconductor electrode, and formation of a positive space charge (or depletion) region with the depletion width of W_n in the n -type semiconductor electrode. The space charge distribution across the p - n junction can be illustrated in figure 2A and expressed with the following expression:

$$\rho(x) = \begin{cases} +qN_D & \text{for } 0 \leq x \leq W_n \\ -qN_A & \text{for } -W_p \leq x \leq 0 \end{cases} \quad (1)$$

where N_A is the acceptor concentration in first electrode 10; N_D is the donor concentration in n -type semiconductor in second electrode 20; The electric potential $\psi(x)$ and electric field $E(x)$ in the space charge regions can be determined using the Poisson equation and can be expressed with the following expression,

$$\frac{d^2\psi}{dx^2} = -\frac{\rho(x)}{\epsilon_0\epsilon_r} \quad (2)$$

and the boundary conditions of $E(x = W_n) = E(x = -W_p) = 0$ and $\psi(x = 0^-) = \psi(x = 0^+)$. With the chemical potential difference $V_B = \psi(x = W_n) - \psi(x = -W_p)$ which is also under thermal equilibrium, the relation among V_B , W_p and W_n can be expressed in the following expression:

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$$V_B = \frac{qN_D W_n^2}{2\epsilon_0 \epsilon_r} + \frac{qN_A W_p^2}{2\epsilon_0 \epsilon_r} \quad (3)$$

where N_A is the acceptor concentration in first electrode 10; N_D is the donor concentration in second electrode 20; ϵ_0 is the permittivity of free space; ϵ_r is the dielectric constant of the semiconductor. Equation (3) above indicates that V_B is fully dropped to the two depletion regions and the space charge is $Q_S = qAW_n N_D = qAW_p N_A$. This means that equation (3) can also be expressed in the following manner:

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$$V_B = \frac{Q_S(W_n + W_p)}{2\epsilon_0 \epsilon_r} \quad (4)$$

Under thermal equilibrium, no current flows across the junction and through the external circuit and the energy band diagram can be shown above the two electrodes 10 and 20 in figure 1B.

20 Once the two electrodes 10, 20 are being separated with mechanical power (i.e. the separating stage), the space charges (or the diffused electrons) discharge to external circuit, yielding a negative transient current i flowing from the n -type to p -type semiconductor electrode through the external load resistance R , converting mechanical power to electrical power. As a part of V_B drops to the air gap and the external load resistance R , the depletion regions shrink significantly once the electrodes 10, 20 are separated. The energy band diagram for the separating stage can be shown in figure 1C. After the gap width d reaches to its maximum d_f and the relative motion of the two electrodes is stopped (i.e. the separated stage which is shown in figure 1D), the electron pump reaches another thermal equilibrium with the new depletion width w_p and w_n . The space charge distribution can be
30 illustrated in figure 2B and expressed with the following expression:

$$\rho(x) = \begin{cases} +qN_D & \text{for } d_f \leq x \leq d_f + W_n \\ 0 & \text{for } 0 \leq x < d_f \\ -qN_A & \text{for } -W_p \leq x < 0 \end{cases} \quad (5)$$

Using the Poisson equation (equation (2) above) and the boundary conditions of $E(x = d_f + w_n) = E(x = -w_p) = 0$ and $\psi(x = 0^-) = \psi(x = 0^+)$ and $\psi(x = d_f^-) = \psi(x = d_f^+)$. With the chemical potential difference $V_B = \psi(x = d_f + W_n) - \psi(x = -W_p)$, the relation among V_B , W_p and W_n can be expressed in the following expression:

$$V_B = \frac{qN_D w_n^2}{2\varepsilon_0 \varepsilon_r} + \frac{qN_A w_p^2}{2\varepsilon_0 \varepsilon_r} + \frac{qN_D w_n d_f}{\varepsilon_0} \quad (6)$$

The first two terms on the right side of equation (6) indicate that V_B drops to the depletion regions in the two semiconductor electrodes, while the last term stands for V_B drop across the air gap. The charge in the depletion regions equals the total space charge in the electrodes, i.e. the space charge reduces to $Q_S' = qA w_n N_D = qA w_p N_A$. Hence, equation (6) can also be expressed as follows:

$$V_B = \frac{Q_S'(w_n + w_p)}{2\varepsilon_0 \varepsilon_r} + \frac{Q_S' d_f}{\varepsilon_0} \quad (7)$$

The amount of the charge that has been 'pumped' to the circuit during the electrode separation can be determined using equations (4) and (7):

$$\Delta Q = Q_S - Q_S' = Q_S \left(1 - \frac{W_n + W_p}{w_n + w_p + 2\varepsilon_r d_f} \right) = Q_S \left(1 - \frac{W}{W + 2\varepsilon_r d_f} \right) \quad (8)$$

where $W = W_n + W_p$ and $w = w_n + w_p$. As $\varepsilon_r = 10 \sim 20$ for most of the semiconductors, the total discharged charge $\Delta Q = (95\% \sim 98\%)Q_S$, when $d_f \sim W$. In other words, when the two electrodes are separated with a gap width comparable to the width of the space charge regions, most of the space charges (or the diffused electrons) can be discharged or 'pumped' out to the circuit as illustrated in figure 1D.

In the approaching stage, the two electrodes are moved toward each other till they are brought into contact. The space charge regions in the electrodes are restored in two processes. The first process is via the electrostatic induction by the chemical potential difference through the external circuit. This restoration is restrained by R with a time constant of RC , leading to a positive transient current flowing from the p - to n -type semiconductor electrode. This is the process that restores the space charge in other electrostatic generators. More interestingly, in the second process, the space charge regions can be restored through diffusion of electrons from the second electrode 20 to first electrode 10 once the two electrodes are in contact, accompanied by establishment of the built-in electric field which retards the diffusion till thermal equilibrium. As this process takes place only across the contacted surfaces, it would neither induce a significant current in the external circuit nor be affected by RC . Note that the drift time for electrons across the p - n junction can be estimated as $\tau_{dri} \sim \varepsilon_r W^2 / \mu_n V_B$, where μ_n is the mobility for electrons. For a conventional silicon based p - n junction, $\mu_n \sim 10^3 \text{ cm}^2/\text{Vs}$, $W \sim 1 \text{ }\mu\text{m}$, $V_B \sim 1 \text{ V}$ and $\varepsilon_r \sim 10$, we have $\tau_{dri} \sim 10^{-10} \text{ s}$. Actual re-establishment of the space charge regions may take more time than τ_{dri} , but the process may not be much slower as it is dominated by diffusion of majority carriers, rather than minority ones. If the RC is larger than the time needed to complete the approaching stage, the space charge regions could not be fully restored in this stage and then the rest charge restoration must proceed with electron diffusion process after the electrodes are in contact. The electron diffusion process occurs across the two contacted second surfaces of the two electrodes 10, 20 and does not cause a detectable current in the external circuit. As a result, only a small positive pulse current or a small amount of integrated charge $Q_{\text{int-pos}} \left(= \int_0^{t\text{-pos}} i dt \right)$, where $t\text{-pos}$ is the time duration of the positive pulse current) is expected. In comparison, a larger negative pulse current or a large integrated charge $Q_{\text{int-neg}} \left(= \left| \int_0^{t\text{-neg}} i dt \right| \right)$ (where $t\text{-neg}$ is the time duration of the negative pulse current) could be obtained in the separating stage as it is caused by discharging the diffused electrons and electrostatically induced charges. $\Delta Q_{\text{int}} = Q_{\text{int-neg}} - Q_{\text{int-pos}}$ should correspond to the amount of diffused electrons across the contacted surfaces. With increasing R , ΔQ_{int} is expected to increase as well. In repeatable electrode motion cycles, the electrons that could diffuse across the contacted surfaces under the

impact of the chemical potential energy difference could also be “pumped” out by the mechanical power to flow in the external circuit. In other words, the electron pumps generate both conduction current and displacement current.

- 5 Several electrode pairs of semiconductor & semiconductor (S&S) and metal & semiconductor (M&S) have been studied. In one S&S electrode pair, a boron doped p^+ -type (100) silicon substrate ($\rho \sim 5 \times 10^{-3} \Omega \cdot \text{cm}$, $N_A \sim 5 \times 10^{19} \text{ cm}^{-3}$) and a phosphorus doped n -type (100) silicon substrate ($\rho \sim 5 \Omega \cdot \text{cm}$, $N_D \sim 2 \times 10^{15} \text{ cm}^{-3}$) were cut into $2.0 \times 2.0 \text{ cm}^2$, cleaned and coated with the back metal pads. The first electrode (the p^+ -type) was attached
 10 to a linear motor (LinMot E1100-GP) controlled translation stage, while the second electrode (the n -type) was fixed to an immovable holder. The relative motion of the two electrodes was controlled by the translation stage.

In the contacted stage (4), a good rectification characteristic curve was obtained as shown
 15 in the bottom left inset 50 in figure 3, suggesting that a p - n junction was formed. Using the variable capacitance method, $V_B' = 0.28 \text{ V}$ was determined. The two electrodes were connected through a load resistor of $50 \text{ M}\Omega$ (as shown in the bottom right inset 51 in figure 3).

- 20 When the two electrodes were being separated from $d=0$ to 2.5 mm in 85 ms , e.g. in the separating stage (1), a negative pulse current 310 flowed from the n -type to p^+ -type silicon electrode (as shown by reference C in figure 3). When the separation gap reached the maximum of $d_f = 2.5 \text{ mm}$ (in the separated stage (2)), the current decayed to zero 320 rapidly. In the approaching stage (3), the gap d was reduced from 2.5 mm to zero in 85 ms and only a small positive pulse current 330 was observed. $\Delta Q_{\text{int}} = Q_{\text{int-neg}} - Q_{\text{int-pos}} \approx$
 25 $Q_{\text{int-neg}} = 6.1 \times 10^{-11} \text{ C}$ and $Q_{\text{int-neg}} / Q_{\text{int-pos}} \sim 4.7$. The voltage dropped to R (as shown by reference B in figure 3) was consistent with the current (as shown by reference C in figure 3). It is noted that the voltage signal (as shown by reference B in figure 3) to noise ratio was much poorer than that of the current. As discussed above, $\Delta Q_{\text{int}} = Q_{\text{int-neg}} - Q_{\text{int-pos}}$
 30 would increase with increasing R . Here, a clear trend can be seen from figure 4 where the influences of R on the transient current (as shown on the left of figure 4) and integrated charge (as shown on the top right of figure 4) are displayed. With increasing R , $Q_{\text{int-neg}}$

410 maintained at $\sim 6 \times 10^{-11}$ C, but $Q_{\text{int-pos}}$ 420 gradually decreased, especially when $R > 1$ M Ω . $Q_{\text{int-neg}} / Q_{\text{int-pos}}$ and Q_{int} increased from 1.1 and 6.6×10^{-12} C under $R=0$ Ω to nearly infinity and 5.9×10^{-11} C under $R = 1$ G Ω , respectively. The average peak power delivered onto R can be determined using $\bar{P} = R \int_0^{t_s} i^2 dt / t_s$, where t_s is the time duration
 5 of the pulse current. From bottom right of figure 4, the average peak power for the negative pulse current $\bar{P}_{n\text{-pulse}}$ 430 (and the positive pulse current $\bar{P}_{p\text{-pulse}}$ 440) shows a maximum value of 31 pW at $R \sim 100$ M Ω (and 0.96 pW at $R \sim 10$ M Ω), suggesting the current caused by discharging the diffused electrons dominates the electric power on the load resistor.

10 The electron pumps can also be constructed with M&S electrode pairs. The current and voltage responses from a pair of a highly phosphorus doped n^+ -type (100) silicon ($\rho \sim 5 \times 10^{-3}$ $\Omega \cdot \text{cm}$, $N_D \sim 2 \times 10^{19}$ cm^{-3}) and gold electrodes are shown on the bottom right inset 54 in figure 5. The gold electrode was fabricated by coating 10-nm Ti and 1- μm Au on a
 15 silicon supporting substrate. The contacting areas of the electrodes were $\sim 2.0 \times 2.0$ cm^2 . The rectification characteristic (as shown on the bottom left inset 53 of figure 5) indicates that a good Schottky junction was formed in the contacted stage (4), leaving a positive space charge region in the n^+ -type silicon electrode. In the separating stage (1), a clear negative pulse current 510 from the n^+ -type silicon electrode to the gold electrode through
 20 a load resistance of 50 M Ω was detected (as shown by reference C in figure 5). Similar to the S&S electrodes discussed above, only a very small positive pulse current 530 in the approaching stage was detected. Except for a much poorer signal to noise ratio, the voltage response (as shown by reference B in figure 5) was consistent with the current response (as shown by reference C in figure 5). From the current response as a function of R (as
 25 shown on the left of figure 6), one can see that $Q_{\text{int-neg}}$ 610 varied from 3.0×10^{-10} to 3.5×10^{-10} C for a wide range of R (as shown on the top right of figure 6). $Q_{\text{int-pos}}$ 620 was comparable to $Q_{\text{int-neg}}$ 610 for $R \sim 1$ M Ω and it decreased significantly with increasing R for $R > 1$ M Ω . At $R = 50$ M Ω , $Q_{\text{int-neg}} / Q_{\text{int-pos}} \sim 6$ and $\Delta Q_{\text{int}} \sim 2.7 \times 10^{-10}$ C (as shown on the top right of figure 6). The finding suggests that discharging of the diffused electrons
 30 does dominate the negative pulse current for large R . As shown on the bottom right of figure 6, $\bar{P}_{n\text{-pulse}}$ 630 (and $\bar{P}_{p\text{-pulse}}$ 640) showed a maximum value of 5.3 nW at $R \sim 10$ M Ω

(and 0.52 nW at $R \sim 4 \text{ M}\Omega$), indicating that the power delivered to the load was dominated by discharging the diffused electrons.

It is noted that the electrode area does not affect the characteristic of the current response, but it does change the current amplitude. $Q_{\text{int-neg}} > Q_{\text{int-pos}}$ was confirmed for all 4 areas (of 2.0×2.0 , 1.5×1.5 , 1.0×1.0 and $0.5 \times 0.5 \text{ cm}^2$), while both $Q_{\text{int-neg}}$ and $Q_{\text{int-pos}}$ increased with the area in roughly linear relations (as shown in figure 7). In addition, studies have been conducted for several other electrode pairs with apparent chemical potential differences, such as *p*-type Si & *n*-type Si, *p*-type Si & n^+ -type Si, p^+ -type Si & n^+ -type Si, Au & *n*-type Si, *p*-type Si & Al and p^+ -type Si & Al and Au & Al electrode pairs. Their current responses showed similar characteristic as shown in figure 3 and figure 5, suggesting that electrons could directly diffuse from the higher to the lower chemical potential electrode once they are brought into contact. The diffusion process plays a role of efficiently charging the capacitor between the two electrodes and it can be much faster than a pure *RC* charging process. In this sense, the electron pumps according to this disclosure could work at high mechanical vibration frequencies. Since doped semiconductors can be directly utilized as the electrodes, the electron pumps can be easily integrated with other semiconductor devices and IC chips to function as a power source or mechanical sensing nodes.

The details of the two electrodes pairing will now be described as follows.

First embodiment

In a first embodiment and with reference to figures 8-11, the energy harvester for converting mechanical energy into electrical energy comprises a first electrode 10, a second electrode 20 and a load *R*. The first electrode 10 comprises an *n*-type semiconductor material 101. A low work-function metal 103 is coated on the first end of the first electrode 10 achieve a small contact resistance. Alternatively, the low work-function metal 103 is coated to the back of the *n*-type semiconductor material 101 to achieve a small contact resistance as shown in figures 8-11. One skilled in the art will recognise that the low work function metal 103 aims to achieve a small contact resistance

between the n-type semiconductor material 101 and the external connection 105, as shown in figures 8-11.

The second electrode 20 comprises a p-type semiconductor material 102. A high work-function metal 104 is coated on the first end of the second electrode 20 achieve a small contact resistance. Alternatively, the high work-function metal 104 is coated to the back of the p-type semiconductor material 102 to achieve a small contact resistance. One skilled in the art will recognise that the high work function metal 104 aims to achieve a small contact resistance between the p-type semiconductor material 102 and the external connection 105, as shown in figures 8-11.

The first electrode 10 and the second electrode 20 are electrically connected through the external connection 105 and load R . When the second end of the first electrode 10 and the second end of the second electrode 20 are in contact, a region of negative space charges 107 is formed in the p-type semiconductor material 102 in the second electrode 20 due to the diffusion of electrons from the n-type semiconductor material 101 to the p-type semiconductor material 102 and, concurrently, a region of positive space charges 106 is formed in the n-type semiconductor material 101 due to the diffusion of holes from the p-type semiconductor material 102 to the n-type semiconductor material 101 when the first electrode 10 is in contact with the second electrode 20 as shown in figure 9. A transient current flow (as shown by the direction of the current flow in figure 10) is generated once the two electrodes 10, 20 are being separated due to the potential difference across the two space charge regions 106 and 107, driving the diffused electrons to flow back to the first electrode 10 through the external connection 105 with a load R (as shown by the direction of the electron flow in figure 10).

Passivation layers may be introduced to passivate the electrode surface and reduce surface charges of the semiconductors. With reference to figure 12, a first passivation layer 61061 is provided on the first electrode 10. The first electrode 10 is being arranged such that the n-type semiconductor material 101 is between the first passivation layer 61061 and the low work function metal 103. A second passivation layer 61062 is provided on the second electrode 20. The second electrode 20 is being arranged such that the p-type semiconductor material 102 is between the second passivation layer 61062 and the high

work function metal 104. The passivation layers 61061 and 61062 comprise ultrathin (for example, in few nanometers) low and high work function metals or ultrathin dielectric materials.

- 5 The method for providing the first embodiment can be described in the following manner and with reference to figure 13. The process 1700 begins with step 1705 where a first electrode 10 is provided. The first electrode 10 comprises an n-type semiconductor material 101 whose backside is coated with a low work-function metal 103 to maintain a low contact resistance to the external connection 105. In step 1710, a second electrode 20 is provided. The second electrode 20 comprises a p-type semiconductor material 102 whose backside is coated with a high work-function metal 104 to maintain a low contact resistance to the external connection 105.

15 In step 1715, the first electrode 10 and the second electrode 20 are connected to the external circuit 105 with a load R. In particular, the first end of the load is connected to the first end of the first electrode 10 and the second end of the load is connected to the first end of the second electrode 20.

20 In step 1720, a transient current flow is generated due to relative movement of the first and second electrodes 10, 20. Specifically, when the two electrodes 10, 20 contact each other (the contacted stage), electrons in the n-type semiconductor material 101 diffuse to the p-type semiconductor material 102 as the n-type semiconductor material 101 has a higher Fermi level than the p-type semiconductor material 102, leaving behind positively charged space charges in the n-type semiconductor material 101. As a result, a negatively charged space charge (or depletion) region 107 is formed in the p-type semiconductor material 102 near the interface and a positively charged space charge (or depletion) region 106 is formed in the n-type semiconductor material 101 near the interface. The positively and negatively charged space charge regions 106, 107 create an electric field pointing from the positive charge region to the negative region. Under the thermal equilibrium condition, 25 the n-type semiconductor material 101 has a higher potential than the p-type semiconductor material 102, preventing electrons from further diffusion. Thus there is no current in the external circuit (the contacted state as shown in figure 9). However, when the two electrodes 10, 20 are being separated, the electrons diffused from the n-type 30

semiconductor material 101 to the p-type semiconductor material 102 flow through the external connection 105 with the load R back to the n-type semiconductor material 101 because of the potential difference, generating a transient current flowing from the n-type semiconductor material 101 to the p-type semiconductor material 102 (the separating state as shown in figure 10). When the two electrodes 10, 20 are separated and the relative motion stop, the two electrodes 10, 20 and the circuit reach another thermal equilibrium condition. Most of the electrons flow back to the n-type semiconductor material 101. No current flows in the external connection 105 when in the separated stage as shown in figure 11.

Second embodiment

In a second embodiment and with reference to figures 14-17, the energy harvester for converting mechanical energy into electrical energy comprises a first electrode 10, a second electrode 20 and a load R. This embodiment implements the metal and semiconductor pairing.

The first electrode 10 comprises an n-type semiconductor material 2011. A low work function metal 2031 is coated on the first end of the first electrode 10 achieve a small contact resistance. Alternatively, the low work function metal 2031 is coated to the back of the n-type semiconductor material 2011 to achieve a small contact resistance to external connection 205. One skilled in the art will recognise that the low work function metal 2031 aims to achieve a small contact resistance between the n-type semiconductor material 2011 and the external connection 205, as shown in figures 14-17.

The second electrode 20 of the second embodiment comprises a high work function metal 2021.

The first electrode 10 and the second electrode 20 are electrically connected through the external connection 205 with a load R. When the second end of the first electrode 10 and the second end of the second electrode 20 are in contact, as shown in Figure 15, a region of positive space charges 2061 is formed in the n-type semiconductor material 2011 due to electron transfer from the n-type semiconductor material 2011 to the high work function metal 2021 of the second electrode 20 because of the work function difference between

the two materials. A transient current flow is generated due to the potential difference across the space charge region 2061 in the n-type semiconductor material 2011 and the high work function metal 2021, which drives the transferred electrons to flow back to the n-type semiconductor material 2011 through the external connection 205 with the load R when the two electrodes 10, 20 are being separated as shown in figure 16.

Passivation layers may be introduced to passivate the electrode surface and reduce surface charges of the semiconductors. With reference to figure 18, a first passivation layer 62061 is provided on the first electrode 10. The first electrode 10 is being arranged such that the n-type semiconductor material 2011 is between the first passivation layer 62061 and the low work function metal 2031. The passivation layer 62061 comprises ultrathin (for example, in few nanometers) low and high work function metals or ultrathin dielectric materials.

The method for providing the second embodiment can be described in the following manner and with reference to figure 13. The process 1700 begins with step 1705 where a first electrode 10 is provided. As mentioned above, the first electrode 10 comprises an n-type semiconductor material 2011 and a low work function metal 2031 coated on the first end of the first electrode 10 achieve a small contact resistance.

In step 1710, a second electrode 20 is provided. The second electrode 20 of the second embodiment comprises a high work function metal 2021.

In step 1715, the first electrode 10 and the second electrode 20 are connected through the external connection 205 with a load R. In particular, the first end of the load is connected to the first end of the first electrode 10 and the second end of the load is coupled to the first end of the second electrode 20.

In step 1720, a transient current flow is generated due to relative movement of the first and second electrodes 10, 20. Specifically, in the contacted stage as shown in figure 15, electrons in the n-type semiconductor material 2011 diffuse to the high work function metal 2021, leaving behind positive space charges, as the n-type semiconductor material 2011 has a higher Fermi level than the high work function metal 2021. As a result, a

positively charged space charge (or depletion) region 2061 is formed in the n-type semiconductor material 2011, while the diffused electrons accumulate on the surface of the high work function metal 2021. The positive and negative charges create an electric field pointing from the positively charged space charge region 2061 to the surface of the high work function metal 2021. Under the thermal equilibrium condition, the n-type semiconductor material 2011 has a higher potential than the high work function metal 2021, preventing electrons from further diffusion. There is no current in the external connection 205 with a load R when in the contacted stage as shown in figure 15. However, when the two electrodes 10, 20 are being separated, the electrons diffused from the n-type semiconductor material 2011 to the high work function metal 2021 flow through the external connection back to the n-type semiconductor material 2011 because of a potential difference between the two electrodes, generating a flow of electrons from the high work function metal 2021 to the n-type semiconductor material 2011 or a current flow from the first electrode 10 to the second electrode 20 during the separating stage as shown in figure 16. After the relative motion of the two electrodes is stopped, most of the electrons flow back to the n-type semiconductor material 2011 and the two electrodes 10, 20 reach the thermal equilibrium condition again. No current flows in the external connection with the load R when in the separated state as shown in figure 17.

Alternative second embodiment

Figure 19 illustrates an alternative embodiment of the second embodiment. In this embodiment, the first electrode 10 comprises a p-type semiconductor material 2012. A high work function metal 2032 is coated on the first end of the first electrode 10 to achieve a small contact resistance. Alternatively, the high work function metal 2032 is coated to the back of the p-type semiconductor material 2012 to achieve a small contact resistance to external connection 205. One skilled in the art will recognise that the high work function metal 2032 aims to achieve a small contact resistance between the p-type semiconductor material 2012 and the external connection 205, as shown in figure 19. The second electrode 20 comprises a low work function metal 2022.

The first electrode 10 and the second electrode 20 are electrically connected through the external connection 205 with a load R. When the second end of the first electrode 10 and the second end of the second electrode 20 are in contact, a region of negative space

charges is formed in the p-type semiconductor material 2012 due to electron transfer from the low work function metal 2022 of the second electrode 20 to the p-type semiconductor material 2012 because of the work function difference between the two materials. A transient current is generated, flowing from the second electrode 20 to the first electrode 10, due to the potential difference across the space charge region in the p-type semiconductor material 2012 and the low work function metal 2022, which drives the transferred electrons to flow back to the second electrode 20 through the external connection 205 with the load R when the two electrodes 10, 20 are being separated.

Passivation layers may be introduced to passivate the electrode surface and reduce surface charges of the semiconductors. With reference to figure 20, a first passivation layer 62062 is provided on the first electrode 10. The first electrode 10 is being arranged such that the p-type semiconductor material 2012 is between the first passivation layer 62062 and the high work function metal 2032. The passivation layer 62062 comprises ultrathin (for example, in few nanometers) low and high work function metals or ultrathin dielectric materials.

The method for providing the alternative second embodiment can be described in the following manner and with reference to figure 13. The process 1700 begins with step 1705 where a first electrode 10 is provided. As mentioned above, the first electrode 10 comprises a p-type semiconductor material 2012 and a high work function metal 2032 is coated on the first end of the first electrode 10 achieve a small contact resistance.

In step 1710, a second electrode 20 is provided. The second electrode 20 comprises a low work function metal 2022.

In step 1715, the first electrode 10 and the second electrode 20 are connected through the external connection 205 with a load R. In particular, the first end of the load is connected to the first end of the first electrode 10 and the second end of the load is connected to the first end of the second electrode 20.

In step 1720, a transient current flow is generated due to relative movement of the first and second electrodes 10, 20. Specifically, in the contacted stage, a region of negative space

charges is formed in the p-type semiconductor material 2012 due to electron transfer from the low work function metal 2022 of the second electrode 20 to the p-type semiconductor material 2012 because of the work function difference between the two materials. When the two electrodes 10, 20 are being separated, a transient current is generated, flowing from the second electrode 20 to the first electrode 10, due to the potential difference across the space charge region in the p-type semiconductor material 2012 and the low work function metal 2022, which drives the transferred electrons to flow back to the second electrode 20 through the external connection 205 with the load R.

Third embodiment

In a third embodiment and with reference to figure 21, the energy harvester for converting mechanical energy into electrical energy comprises a first electrode 10, a second electrode 20 and a load R. This embodiment implements the pairing of two semiconductors.

The first electrode 10 comprises an n-type semiconductor material 30111 and a p-type semiconductor material 30112. A p-n junction (e.g. comprising a region of positive space charges 3071 and a region of negative space charges 3081) is formed between the n-type semiconductor material 30111 and p-type semiconductor material 30112. A low work function metal 3031 is coated on the first end of the first electrode 10 achieve a small contact resistance. Alternatively, the low work function metal 3031 is coated to the back of the n-type semiconductor material 30111 to achieve a small contact resistance. The first electrode 10 is being arranged such that the n-type semiconductor material 30111 is between the p-type semiconductor material 30112 and the low work function metal 3031. One skilled in the art will recognise that the low work function metal 3031 aims to achieve a small contact resistance between the n-type semiconductor material 30111 and the external connection 305, as shown in figure 21.

The second electrode 20 comprises an n-type semiconductor material 3021. A low work function metal 3041 is coated on the first end of the second electrode 20 achieve a small contact resistance. Alternatively, the low work function metal 3041 is coated to the back of the n-type semiconductor material 3021 to achieve a small contact resistance. One skilled in the art will recognise that the low work function metal 3041 aims to achieve a

small contact resistance between the n-type semiconductor material 3021 and the external connection 305, as shown in figure 21.

The first electrode 10 and the second electrode 20 are electrically connected through the external connection 305 with a load R. When the second end of the first electrode 10 and the second end of the second electrode 20 are in contact, a region of positive space charges is formed in the n-type semiconductor material 3021 in the second electrode 20 due to the diffusion of holes from the p-type semiconductor material 30112 in the first electrode 10 to the n-type semiconductor material 3021 in the second electrode 20. Concurrently, a region of negative space charges is formed in the p-type semiconductor material 30112 of the first electrode 10 due to the diffusion of electrons from the n-type semiconductor material 3021 in the second electrode 20 to the p-type semiconductor material 30112 in the first electrode 10 when the first electrode 10 is in contact with the second electrode 20. A transient current flow is generated, flowing from the second electrode 20 to the first electrode 10, due to the potential difference across the two space charge regions in the two electrodes 10, 20, which drives the diffused electrons to flow back to the second electrode 20 through the external connection 305 and load R when the first electrode 10 and the second electrode 20 are being separated. It is noted that the p-n junction in the first electrode 10 could accelerate the restoration and reach the thermal equilibrium condition more quickly than the first and second embodiments.

Passivation layers may be introduced to passivate the electrode surface and reduce surface charges of the semiconductors. With reference to figure 22, a first passivation layer 630612 is provided on the first electrode 10. The first electrode 10 is being arranged such that the p-type semiconductor material 30112 is between the first passivation layer 630612 and n-type semiconductor material 30111. A second passivation layer 630611 is provided on the second electrode 20. The second electrode 20 is being arranged such that the n-type semiconductor material 3021 is between the second passivation layer 630611 and the low work function metal 3041. The first and second passivation layers 630612 and 630611 comprise ultrathin (for example, in few nanometers) low and high work function metals or ultrathin dielectric materials.

The method for providing the third embodiment can be described in the following manner and with reference to figure 13. The process 1700 begins with step 1705 where a first electrode 10 is provided. As mentioned above, the first electrode 10 comprises an n-type semiconductor material 30111 and a p-type semiconductor material 30112 forming a p-n junction 3071 and 3081 between the n-type semiconductor material 30111 and p-type semiconductor material 30112. A low work function metal 3031 is coated on the first end of the first electrode 10 achieve a small contact resistance.

In step 1710, a second electrode 20 is provided. The second electrode 20 comprises an n-type semiconductor material 3021. A low work function metal 3041 is coated on the first end of the second electrode 20 achieve a small contact resistance.

In step 1715, the first electrode 10 and the second electrode 20 are connected through the external connection 305 with a load R. In particular, the first end of the load is connected to the first end of the first electrode 10 and the second end of the load is connected to the first end of the second electrode 20.

In step 1720, a transient current flow is generated due to relative movement of the first and second electrodes 10, 20. Specifically, in the contacted stage, a region of positive space charges is formed in the n-type semiconductor material 3021 in the second electrode 20 due to the diffusion of holes from the p-type semiconductor material 30112 in the first electrode 10 to the n-type semiconductor material 3021 in the second electrode 20. Concurrently, a region of negative space charges is formed in the p-type semiconductor material 30112 of the first electrode 10 due to the diffusion of electrons from the n-type semiconductor material 3021 in the second electrode 20 to the p-type semiconductor material 30112 in the first electrode 10. When the two electrodes are being separated, a transient current flow is generated, flowing from the second electrode 20 to the first electrode 10, due to the potential difference across the two space charge regions in the two electrodes, which drives the diffused electrons to flow back to the second electrode 20 through the external connection 305 and load R.

Alternative third embodiment

Figure 23 illustrates an alternative embodiment of the third embodiment. The first electrode 10 comprises a p-type semiconductor material 30121 and an n-type semiconductor material 30122. A high work function metal 3032 is coated on a first end of the first electrode 10. The first electrode 10 is being arranged such that the p-type semiconductor material 30121 is between the n-type semiconductor material 30122 and the high work function metal 3032. A positive space charge (or depletion) region 3082 is formed in the n-type semiconductor material 30122 and a negative space charge (or depletion) region 3072 is formed in p-type semiconductor material 30121, thus forming a p-n junction in the first electrode 10. The second electrode 20 comprises a p-type semiconductor material 3022 and a high work function metal 3042. The high work-function metal 3042 is coated onto the first end of the second electrode 20. The high work-function metal 3042 is coated to the back of the p-type semiconductor material 3022 to achieve a small contact resistance.

The first electrode 10 and the second electrode 20 are electrically coupled through the external connection 305 with a load R. When the second end of the first electrode 10 and the second end of the second electrode 20 are in contact, a region of positive space charges is formed in the n-type semiconductor material 30122 in the first electrode 10 due to the diffusion of holes from the p-type semiconductor material 3022 in the second electrode 20 to the n-type semiconductor material 30122 in the first electrode 10. Concurrently, a region of negative space charges is formed in the p-type semiconductor material 3022 of the second electrode 20 due to the diffusion of electrons from the n-type semiconductor material 30122 in the first electrode 10 to the p-type semiconductor material 3022 in the second electrode 20 when the first electrode 10 is in contact with the second electrode 20. A transient current flow is generated, flowing from the first electrode 10 to the second electrode 20, due to the potential difference across the two space charge regions in the two electrodes 10, 20, which drives the diffused electrons to flow back to the first electrode 10 through the external connection 305 and load R when the first electrode 10 and the second electrode 20 are being separated. It is noted that the p-n junction in the first electrode 10 could accelerate the restoration and reach the thermal equilibrium condition more quickly than the first and second embodiments.

Passivation layers may be introduced to passivate the electrode surfaces and reduce surface charges of the semiconductors. With reference to figure 24, a first passivation layer 630621 is provided on the first electrode 10. The first electrode 10 is being arranged such that the n-type semiconductor material 30122 is between the first passivation layer 630621 and p-type semiconductor material 30121. A second passivation layer 630622 is provided on the second electrode 20. The second electrode 20 is being arranged such that the p-type semiconductor material 3022 is between the second passivation layer 630622 and the high work function metal 3042. The first and second passivation layers 630621 and 630622 comprise ultrathin (for example, in few nanometers) low and high work function metals or ultrathin dielectric materials.

The method for providing the alternative embodiment of the third embodiment can be described in the following manner and with reference to figure 13. The process 1700 begins with step 1705 where a first electrode 10 is provided. As mentioned above, the first electrode 10 comprises a high work function metal 3032, a p-type semiconductor material 30121 and an n-type semiconductor material 30122. The first electrode 10 is being arranged such that the p-type semiconductor material 30121 is between the n-type semiconductor material 30122 and the high work function metal 3032. The high work-function metal 3032 is coated to the back of the p-type semiconductor material 30121 to achieve a small contact resistance.

In step 1710, a second electrode 20 is provided. The second electrode 20 comprises a p-type semiconductor material 3022 and a high work function metal 3042. The high work-function metal 3042 is coated to the back of the p-type semiconductor material 3022 to achieve a small contact resistance.

In step 1715, the first electrode 10 and the second electrode 20 are connected through the external connection 305 with a load R. In particular, the first end of the load is connected to the first end of the first electrode 10 and the second end of the load is connected to the first end of the second electrode 20.

In step 1720, a transient current flow is generated due to relative movement of the first and second electrodes 10, 20. Specifically, in the contacted stage, a region of negative space

charges is formed in the p-type semiconductor 3022 material in the second electrode 20 due to the diffusion of electrons from the n-type semiconductor material 30122 to the p-type semiconductor material 3022. Concurrently, a region of positive space charges is formed in the n-type semiconductor material 30122 due to the diffusion of holes from the p-type semiconductor material 3022 in the second electrode 20. When the two electrodes are being separated, a transient current flow is generated, flowing from the first electrode 10 to the second electrode 20, due to the potential difference across the two space charge regions in the two electrodes 10, 20, which drives the diffused electrons to flow back to the first electrode 10 through the external connection 305 and load R.

Fourth embodiment

In a fourth embodiment and with reference to figure 25, the energy harvester for converting mechanical energy into electrical energy comprises a first electrode 10, a second electrode 20 and a load R.

The first electrode 10 comprises an n-type semiconductor material 40111 and a p-type semiconductor material 40112. A p-n junction (e.g. comprising a region of positive space charges 4071 and a region of negative space charges 4081) is formed between the n-type semiconductor material 40111 and p-type semiconductor material 40112. A low work-function metal 4031 is coated on the first end of the first electrode 10 achieve a small contact resistance. Alternatively, the low work function metal 4031 is coated to the back of the n-type semiconductor material 40111 to achieve a small contact resistance.

The second electrode 20 comprises a metal material. The metal material is a low work function metal 4041.

The first electrode 10 and the second electrode 20 are electrically connected through the external connection 405 with a load R. When the second end of the first electrode 10 and the second end of the second electrode 20 are in contact, a region of negative space charges is formed in the p-type semiconductor material 40112 due to electron transfer from the low work function metal 4041 of the second electrode 20 to the p-type semiconductor material 40112 because of the work function difference between the two materials when the first electrode 10 is in contact with the second electrode 20. A transient

current is generated, flowing from the second electrode 20 to the first electrode 10, due to the potential difference across the space charge region in the p-type semiconductor material 40112 and the low work function metal 4041, which drives the transferred electrons to flow back to the second electrode 20 through the external connection 405 with the load R when the two electrodes 10, 20 are being separated.

Passivation layer may be introduced to passivate the electrode surface and reduce surface charges of the semiconductors. With reference to figure 26, a first passivation layer 64062 is provided on the first electrode 10. The first electrode 10 is being arranged such that the p-type semiconductor material 40112 is between the first passivation layer 64062 and n-type semiconductor material 40111.

The method for providing the fourth embodiment can be described in the following manner and with reference to figure 13. The process 1700 begins with step 1705 where a first electrode 10 is provided. As mentioned above, the first electrode 10 comprises an n-type semiconductor material 40111 and a p-type semiconductor material 40112. A low work-function metal 4031 is coated on the first end of the first electrode 10 achieve a small contact resistance.

In step 1710, a second electrode 20 is provided. The second electrode 20 comprises a low work function metal 4041.

In step 1715, the first electrode 10 and the second electrode 20 are connected through the external connection 405 with a load R. In particular, the first end of the load is connected to the first end of the first electrode 10 and the second end of the load is connected to the first end of the second electrode 20.

In step 1720, a transient current flow is generated due to relative movement of the first and second electrodes 10, 20. Specifically, in the contacted stage, a region of negative space charges is formed in the p-type semiconductor material 40112 due to electron transfer from the low work function metal 4041 of the second electrode 20 to the p-type semiconductor material 40112 because of the work function difference between the two materials. When the two electrodes are being separated, a transient current is generated,

flowing from the second electrode 20 to the first electrode 10, due to the potential difference across the space charge region in the p-type semiconductor material 40112 and the low work function metal 4041, which drives the transferred electrons to flow back to the second electrode 20 through the external connection 405 with the load R.

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Alternative fourth embodiment

Figure 27 illustrates an alternative embodiment of the fourth embodiment. The first electrode 10 comprises an n-type semiconductor material 40122 and a p-type semiconductor material 40121. A high work function metal 4032 is coated on the first end
10 of the first electrode 10. The first electrode 10 is being arranged such that the p-type semiconductor material 40121 is between the n-type semiconductor material 40122 and the high work function metal 4032. A positive space charge (or depletion) region 4082 is formed in the n-type semiconductor material 40122 and a negative space charge (or depletion) region 4072 is formed in p-type semiconductor material 40121, thus forming a
15 p-n junction in the first electrode 10. The second electrode 20 comprises a high work function metal 4042.

The first electrode 10 and the second electrode 20 are electrically connected through the external connection 405 with a load R. When the second end of the first electrode 10 and
20 the second end of the second electrode 20 are in contact, a region of positive space charges is formed in the n-type semiconductor material 40122 due to electron transfer from the n-type semiconductor material 40122 to the high work function metal 4042 of the second electrode 20 because of the work function difference between the two materials when the first electrode 10 is in contact with the second electrode 20. A transient current is
25 generated, flowing from the first electrode 10 to the second electrode 20, due to the potential difference across the space charge region in the n-type semiconductor material 40122 and the high work function metal 4042, which drives the transferred electrons to flow back to the first electrode 10 through the external connection 405 with the load R when the two electrodes 10, 20 are being separated.

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Passivation layers may be introduced to passivate the electrode surface and reduce surface charges of the semiconductors. With reference to figure 28, a first passivation layer 64061 is provided on the first electrode 10. The first electrode 10 is being arranged such that the

n-type semiconductor material 40122 is between the first passivation layer 64061 and p-type semiconductor material 40121. The first passivation layer 64061 comprises ultrathin (for example, in few nanometers) low and high work function metals or ultrathin dielectric materials.

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The method for providing the alternative embodiment of the fourth embodiment can be described in the following manner and with reference to figure 13. The process 1700 begins with step 1705 where a first electrode 10 is provided. As mentioned above, the first electrode 10 comprises an n-type semiconductor material 40122 and a p-type semiconductor material 40121 with a high work function metal 4032 being coated on the first end of the first electrode 10.

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In step 1710, a second electrode 20 is provided. The second electrode 20 comprises a high work function metal 4042.

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In step 1715, the first electrode 10 and the second electrode 20 are connected through the external connection 405 with a load R. In particular, the first end of the load is coupled to the first end of the first electrode 10 and the second end of the load is coupled to the first end of the second electrode 20.

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In step 1720, a transient current flow is generated due to relative movement of the first and second electrodes 10, 20. Specifically, in the contacted stage, a region of positive space charges is formed in the n-type semiconductor material 40122 due to electron transfer from the n-type semiconductor material 40122 to the high work function metal 4042 of the second electrode 20 because of the work function difference between the two materials. A transient current flow is generated, flowing from the first electrode 10 to the second electrode 20, due to the potential difference across the space charge region in the n-type semiconductor material 40122 and the high work function metal 4042, which drives the transferred electrons to flow back to the n-type semiconductor material 40122 through the external connection 405 with the load R when the two electrodes 10, 20 are being separated.

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Fifth embodiment

In a fifth embodiment and with reference to figure 29, the energy harvester for converting mechanical energy into electrical energy comprises a first electrode 10, a second electrode 20 and a load R . This embodiment implements the pairing of two semiconductors.

5 The first electrode 10 comprises an n-type semiconductor material 5011 and a p-type semiconductor material 5012. A p-n junction (e.g. comprising a region of positive space charges 5071 and a region of negative space charges 5081) is formed between the n-type semiconductor material 5011 and p-type semiconductor material 5012. A low work function metal 5031 is coated on the first end of the first electrode 10 to achieve a small
10 contact resistance. Alternatively, the low work function metal 5031 is coated to the back of the n-type semiconductor material 5011 to achieve a small contact resistance. The first electrode 10 is being arranged such that the n-type semiconductor material 5011 is between the p-type semiconductor material 5012 and the low work function metal 5031. One skilled in the art will recognise that the low work function metal 5031 aims to achieve
15 a small contact resistance between the n-type semiconductor material 5011 and the external connection 505, as shown in figure 29.

The second electrode 20 comprises an n-type semiconductor material 5021 and a p-type semiconductor material 5022. A p-n junction (e.g. comprising a region of positive space
20 charges 5091 and a region of negative space charges 5101) is formed between the n-type semiconductor material 5021 and p-type semiconductor material 5022. A high work function metal 5041 is coated on the first end of the second electrode 20 achieve a small contact resistance. Alternatively, the high work function metal 5041 is coated to the back of the p-type semiconductor material 5022 to achieve a small contact resistance. The
25 second electrode 20 is being arranged such that the p-type semiconductor material 5022 is between the n-type semiconductor material 5021 and the high work function metal 5041. One skilled in the art will recognise that the high work function metal 5041 aims to achieve a small contact resistance between the p-type semiconductor material 5022 and the external connection 505, as shown in figure 29.

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The first electrode 10 and the second electrode 20 are electrically connected through the external connection 505 with a load R . When the second end of the first electrode 10 and the second end of the second electrode 20 are in contact, a region of positive space charges

is formed in the n-type semiconductor material 5021 in the second electrode 20 due to the diffusion of holes from the p-type semiconductor material 5012 in the first electrode 10 to the n-type semiconductor material 5021 in the second electrode 20 when the two electrodes are in contact. Concurrently, a region of negative space charges is formed in the p-type semiconductor material 5012 of the first electrode 10 due to the diffusion of electrons from the n-type semiconductor material 5021 in the second electrode 20 to the p-type semiconductor material 5012 in the first electrode 10 when the first electrode 10 is in contact with the second electrode 20. A transient current flow is generated, flowing from the second electrode 20 to the first electrode 10, due to the potential difference across the two space charge regions in the two electrodes, which drives the diffused electrons to flow back to the second electrode 20 through the external connection 505 and load R when the first electrode 10 and the second electrode 20 are being separated. It is noted that the p-n junction in the first electrode 10 and the second electrode 20 could accelerate electron transport process and reach the thermal equilibrium condition more quickly than preceding embodiments.

Passivation layers may be introduced to passivate the electrode surface and reduce surface charges of the semiconductors. With reference to figure 30, a first passivation layer 65062 is provided on the first electrode 10. The first electrode 10 is being arranged such that the p-type semiconductor material 5012 is between the first passivation layer 65062 and n-type semiconductor material 5011. A second passivation layer 65061 is provided on the second electrode 20. The second electrode 20 is being arranged such that the n-type semiconductor material 5021 is between the second passivation layer 65061 and p-type semiconductor material 5022. The first and second passivation layers 65062 and 65061 comprise ultrathin (for example, in few nanometers) low and high work function metals or ultrathin dielectric materials.

The method for providing the fifth embodiment can be described in the following manner and with reference to figure 13. The process 1700 begins with step 1705 where a first electrode 10 is provided. As mentioned above, the first electrode 10 comprises an n-type semiconductor material 5011 and a p-type semiconductor material 5012. A p-n junction 5071 and 5081 is formed between the n-type semiconductor material 5011 and p-type

semiconductor material 5012. A low work function metal 5031 is coated on the first end of the first electrode 10 to achieve a small contact resistance.

In step 1710, a second electrode 20 is provided. The second electrode 20 comprises an n-type semiconductor material 5021 and a p-type semiconductor material 5022. A p-n junction 5091 and 5101 is formed between the n-type semiconductor material 5021 and p-type semiconductor material 5022. A high work function metal 5041 is coated on the first end of the second electrode 20 achieve a small contact resistance.

In step 1715, the first electrode 10 and the second electrode 20 are connected through the external connection 505 with a load R. In particular, the first end of the load is coupled to the first end of the first electrode 10 and the second end of the load is coupled to the first end of the second electrode 20.

In step 1720, a transient current flow is generated due to relative movement of the first and second electrodes 10, 20. Specifically, in the contacted stage, a region of positive space charges is formed in the n-type semiconductor material 5021 in the second electrode 20 due to the diffusion of holes from the p-type semiconductor material 5012 in the first electrode 10 to the n-type semiconductor material 5021 in the second electrode 20.

Concurrently, a region of negative space charges is formed in the p-type semiconductor material 5012 of the first electrode 10 due to the diffusion of electrons from the n-type semiconductor material 5021 in the second electrode 20 to the p-type semiconductor material 5012 in the first electrode 10. When the two electrodes are being separated, a transient current flow is generated, flowing from the second electrode 20 to the first electrode 10, due to the potential difference across the two space charge regions in the two electrodes, which drives the diffused electrons to flow back to the second electrode 20 through the external connection 505 and load R.

In another embodiment, the method for coating the passivation layers, comprises any techniques such as plasma-enhanced chemical vapor deposition (PECVD), molecular beam epitaxy (MBE), laser MBE) that could be used to deposit ultrathin metals or to deposit ultrathin dielectric materials.

The above embodiments can be applied on any two parts where movement of the first and second parts causes the first and second parts to be in contact with each other and subsequently apart from each other. A first application is illustrated by a contact electrode design as shown in figure 31. The structure of the contact electrode design contains a shell 701 and a core 702. The shell 701 and core 702 correspond to the first and second electrodes as described above. When the shell 701 or core 702 is vibrating with respect to the other such that the shell 701 and core 702 are in contact and subsequently apart from each other, the pulsed current would be generated and flow through the load 703.

A second application is illustrated by a sliding electrode design as shown in figure 32. The structure of the sliding electrode design contains a moving part 804 and a stationary part 803. The moving part 804 and stationary part 803 correspond to the first and second electrodes as described above. Alternatively, a plurality of first and second electrodes may be provided on the opposing surface of the moving part 804 and stationary part 803 as referenced by number 802 and 801 respectively. The moving part 804 and stationary part 803 can be fabricated with arrays of semiconductor materials and/or metal pairings on insulating substrates 803 and 804 with appropriate wire connection to the arrays of the patterns. The patterns of the two parts are facing each other. When the moving part 804 moves with respect to the stationary part 803, contact and separation between the patterns 801 and 802 will occur, leading to generating of current flow through a load 805. The movement of the moving part 804 includes vibration, sliding motion and rotation with respect to the stationary part.

In both applications, the electrode surfaces can be passivated with a thin metal layers or/and ultrathin dielectric layers, depending on the doping type of the semiconductors used.

A third application is illustrated by a surface analyser for mapping doping type and concentration of a sample surface as shown in figure 33. This function could be realized through the tapping mode operation of an Atomic Force Microscopy. The tip is preferably made of appropriately doped semiconductors. When the tip is tapping on the surface of a testing sample 902, small pulsed current would be generated. The doping type and doping concentration on the surface of the testing sample 902 can be determined by analysing the

acquired pulsed current magnitude and polarity. Scanning the tapping tip along the sample surface 902, a map of doping type and concentration of a sample surface 902 can be obtained. The semiconductor tip 901 can be passivated with thin metal layers or/and ultrathin dielectric layers, depending on the doping type of the semiconducting tip 901.

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A fourth application is illustrated by a zero energy motion trigger as shown in figure 34. The structure of the motion trigger is similar to the contact electrode design of the mechanical energy harvesters discussed above. It contains a movable mass block 1001 and two fixed electrodes 10021 and 10022. The movable mass block 1001 is positioned in
10 between the two electrodes 10021 and 10022 though two springs 1003. The two fixed electrodes 10021 and 10022 are fixed onto a common frame 1004. When motion occurs in the horizontal direction as shown by the arrow, the movable mass block 1001 will be in contact with the electrodes 10021 and 10022 and subsequently apart from them, causing a pulsed current. This means that the zero energy motion trigger does not need external
15 power. The semiconductor surfaces could be passivated with thin metal layers or/and ultrathin dielectric layers depended on the doping type of the semiconductors used.

While the invention has been illustrated and described in detail in the drawings and foregoing description, such illustration and description are to be considered illustrative or
20 exemplary, and not restrictive; the invention is not limited to the disclosed embodiments. Other variations to the disclosed embodiments can be understood and effected by those skilled in the art in practising the claimed invention.

Claims

1. An energy harvester comprising:

5 a first electrode comprising a first semiconductor material;

a second electrode comprising at least one of a second semiconductor material and a metal material; and

a load between the first and second electrodes electrically connecting a first end of the first electrode and a first end of the second electrode, wherein relative movement of the first electrode and the second electrode causes a second end of the first electrode and a second end of the second electrode to be in contact with each other and subsequently apart from each other generating a current flow through the load.

2. The energy harvester according to claim 1 wherein

15 the first semiconductor material is an n-type semiconductor material and the first end of the first electrode is coated with a low work function metal, and

the second electrode comprises the second semiconductor material, the second semiconductor material is a p-type semiconductor material and the first end of the second electrode is coated with a high work function metal.

3. The energy harvester according to claim 2 wherein

the first electrode further comprises a first passivation layer, the first electrode being arranged such that the n-type semiconductor material is between the first passivation layer and the low work function metal, and

25 the second electrode further comprises a second passivation layer, the second electrode being arranged such that the p-type semiconductor material is between the second passivation layer and the high work function metal.

4. The energy harvester according to claim 1 wherein

30 the first semiconductor material is an n-type semiconductor material, the first end of the first electrode is coated with a low work function metal; and

the second electrode comprises the metal material, the metal material is a high work function metal.

5. The energy harvester according to claim 4 wherein

the first electrode further comprises a passivation layer, the first electrode being arranged such that the n-type semiconductor material is between the passivation layer and the low work function metal.

6. The energy harvester according to claim 1 wherein

the first semiconductor material is a p-type semiconductor material and the first end of the first electrode is coated with a high work function metal; and

the second electrode comprises the metal material, the metal material is a low work function metal.

7. The energy harvester according to claim 6 wherein

the first electrode further comprises a passivation layer, the first electrode being arranged such that the p-type semiconductor material is between the passivation layer and the high work function metal.

8. The energy harvester according to claim 1 wherein

the first semiconductor material comprises an n-type semiconductor material and a p-type semiconductor material, the first end of the first electrode is coated with a low work function metal and the first electrode is being arranged such that the n-type semiconductor material is between the p-type semiconductor material and the low work function metal, and

the second electrode comprises the second semiconductor material and the metal material, the second semiconductor material is an n-type semiconductor material and the metal material is a low work function metal coated onto the first end of the second electrode.

9. The energy harvester according to claim 8 wherein

the first electrode further comprises a first passivation layer, the first electrode being arranged such that the p-type semiconductor material is between the first passivation layer and the n-type semiconductor material, and

the second electrode further comprises a second passivation layer, the second electrode being arranged such that the n-type semiconductor material is between the second passivation layer and the low work function metal.

10. The energy harvester according to claim 1 wherein

the first semiconductor material comprises an n-type semiconductor material and a p-type semiconductor material, the first end of the first electrode is coated with a high work function metal and the first electrode is being arranged such that the p-type semiconductor material is between the n-type semiconductor material and the high work function metal, and

the second electrode comprises the second semiconductor material and the metal material, the second semiconductor material is a p-type semiconductor material, and the metal material is a high work function metal coated onto the first end of the second electrode.

11 The energy harvester according to claim 10 wherein

the first electrode further comprises a first passivation layer, the first electrode being arranged such that the n-type semiconductor material is between the first passivation layer and p-type semiconductor material, and

the second electrode further comprises a second passivation layer, the second electrode being arranged such that the p-type semiconductor material is between the second passivation layer and the high work function metal.

12. The energy harvester according to claim 1 wherein

the first semiconductor material comprises an n-type semiconductor material and a p-type semiconductor material, the first end of the first electrode is coated with a low work function metal and the first electrode is being arranged such that the n-type semiconductor material is between the p-type semiconductor material and the low work function metal; and

the second electrode comprises the metal material, the metal material is a low work function metal.

13 The energy harvester according to claim 12 wherein

the first electrode further comprises a passivation layer, the first electrode being arranged such that the p-type semiconductor material is between the passivation layer and the n-type semiconductor material.

14. The energy harvester according to claim 1 wherein

the first semiconductor material comprises an n-type semiconductor material and a p-type semiconductor material, the first end of the first electrode is coated with a high work function metal and the first electrode is being arranged such that the p-type semiconductor material is between the n-type semiconductor material and the high work function metal;

5 and

the second electrode comprises the metal material, the metal material is a high work function metal.

15 The energy harvester according to claim 14 wherein

10 the first electrode further comprises a passivation layer, the second electrode being arranged such that the n-type semiconductor material is between the passivation layer and p-type semiconductor material.

16. The energy harvester according to claim 1 wherein

15 the first semiconductor material comprises an n-type semiconductor material and a p-type semiconductor material, first end of the first electrode is coated with a low work function metal and the first electrode is being arranged such that the n-type semiconductor material is between the p-type semiconductor material and the low work function metal, and

20 the second electrode comprises the second semiconductor material and the metal material, the second semiconductor material comprises a p-type semiconductor material and an n-type semiconductor material, and the metal material is a high work function metal and the second electrode is being arranged such that the p-type semiconductor material is between the n-type semiconductor material and the high work function metal.

25 17 The energy harvester according to claim 16 wherein

the first electrode further comprises a first passivation layer, the first electrode being arranged such that the p-type semiconductor material is between the first passivation layer and the n-type semiconductor material, and

30 the second electrode further comprises a second passivation layer, the second electrode being arranged such that the n-type semiconductor material is between the second passivation layer and the p-type semiconductor material.

18. A method of harvesting energy comprising:

providing a first electrode comprising a first semiconductor material;

providing a second electrode comprising at least one of a second semiconductor material and a metal material;

5 connecting a first end of a load to a first end of the first electrode and a second end of the load to a first end of the second electrode; and

generating a current flow through the load in response to relative movement of the first electrode and the second electrode such that a second end of the first electrode and a second end of the second electrode are in contact with each other and subsequently apart from each other.

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