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A Hybrid Structure for Energy Harvesting from Human Body Thermal Radiation and Mechanical Movement

Abstract. *In this work, a hybrid structure was proposed to harvest both mechanical and heat energy sources available in the human body. The device is designed to harvest both the thermal radiation of the human body based on the proposed solution-processed photovoltaic structure and the mechanical movement of the human body based on an electrostatic generator. The photovoltaic structure is used to charge the capacitor at the initial step of each conversion cycle. The simple fabrication process of the photovoltaic device can potentially address the problem associated with the charging method of the electrostatic generators. The simulation results showed that the combination of two methods can significantly increase the harvested energy from 2.2 μW/cm^2 in the case of the harvesting thermal energy to 1.47 mW/cm^2 in the case of harvesting both thermal energy and mechanical energy.*

Streszczenie. *Zaproponowano hybrydową strukturę do pozyskiwania mechanicznej I cieplnej energii wytwarzanej przez ciało człowieka. Wykorzystywane jest zjawisko fotowoltaiczne do ładowania kondensatora. Pozyskana energia jest rzędu 2.2 μW/cm^2.* ***Hybrydowa struktura do pozyskiwania energii termicznej i mechanicznej generowanej przez ciało człowieka***

Keywords: Energy harvesting; Thermal energy; Thermal radiation; Energy conversion; Wearable and implantable devices; Mechanical movement.
Słowa kluczowe: pozyskiwanie energii, konwersja enegii, struktiura hybrydowa

Introduction

Vibration is a reliable and available type of energy, especially in the human body. Walking, breathing, and heart beating are some forms of the human body motions providing an abundant source of energy for low-consumption devices. Energy harvester technologies based on triboelectric, piezoelectric, electromagnetic, and electrostatic have been used to convert vibration into electricity. Among these, electrostatic energy harvester, working based on capacitor variation caused by the movable electrode, is the most compatible with microelectromechanical system (MEMS) fabrication process. Technological advances in MEMS have provided a suitable platform for the fabrication of high-performance transducers based on the variable capacitance to harvest mechanical vibration [1-3]. This process can realize a large capacitance variation with a very small-size capacitor. Moreover, electrostatic generators are suitable for low-frequency vibration environments and they can provide a high output voltage and high-power density with small size structure. However, electrostatic generators require a start-up voltage source to charge the capacitor at the initial state of the conversion process, therefore, the generated energy highly depends on the start-up voltage. There are some methods to address this issue such as incorporating an electret in the device structure [2, 4-8], taking advantage of built-in potential generated in the interface surface of two materials with different work function [9], and a self-recharge circuit [10]. Electret, a dielectric material carrying permanent electric charges, is widely used in electrostatic generators to improve the usability and miniaturize the device[11, 12]. Teflon, silicon dioxide (SiO_2), and silicon nitride (Si_3N_4) are some examples of electret materials. However, incorporating electret in the device structure requires a complicated fabrication process [1].

Here, we designed a hybrid energy scavenger. In this structure mechanical movement of the human body is harvested using an electrostatic generator, which required start-up voltage is applied by harvesting human body thermal energy with the photovoltaic device [13]. Since human body thermal energy is a highly available energy source, this structure provides a reliable method to harvest energy. Simple fabrication process of thermal energy harvester addresses drawbacks associated with electret implementation.

Device Structure

The hybrid energy harvester structure, shown in Fig. 1, consists of two parts including photovoltaic device and electrostatic generator. This structure involves six layers: an indium tin oxide (ITO) coated glass substrate; a photosensitive layer composed of 465-nm-thick isopropylamine (IPAM) capped lead sulfide (PbS) colloidal quantum dots (CQDs); a 10-nm-thick lithium chloride (LiCl) layer; an aluminum contact as a negative contact of the device; a 1 μm-thick dielectric layer of oleic acid-capped PbS quantum dots; and a movable aluminum electrode as a positive contact of the structure. The lower part of the device contains a solution-processed photovoltaic structure [13] that is used to harvest thermal radiation of the human body and charge the dielectric layer, located in the upper part, of the generator.

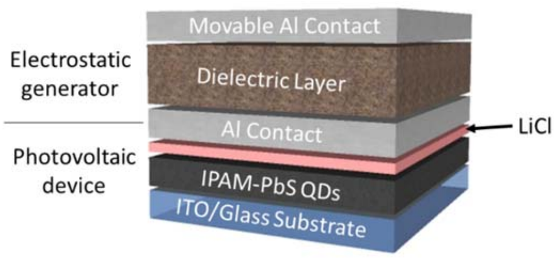

Fig. 1. Device Structure of the hybrid energy scavenger composed of a solution-processed photovoltaic structure (lower part) and an electrostatic generator (upper part).

Working Principles

The proposed hybrid energy harvester employs a solution-processed photovoltaic device in connection with an electrostatic generator. The movable aluminum electrode provides variable capacitance in this structure. Isopropylamine capped PbS quantum dots in photovoltaic structure absorbs thermal radiation of the human body through a multi-step photon absorption process and generates free carriers [13]. The Schottky contact, formed at the interface between aluminum and photosensitive layers of the photovoltaic structure, separates photogenerated carriers toward different contacts. This builds-up electric potential at the photovoltaic device, consequently, at the initial step of the conversion cycle of the electrostatic generator, as shown in Fig. 2(a), where the ITO/Glass substrate is electrically in touch with the movable aluminum electrode, photovoltaic device charges the variable capacitor. In the initial cycle, the variable capacitance is at the maximum value. Then, as result of vibration, the movable aluminum contact of the capacitor detaches from the dielectric layer, which has a high relative permittivity, then moves far away from the other parts of the structure, as shown in Fig. 2 (b), therefore, capacitance decreases. Since there is no change in the amount of charge, the potential difference between electrodes increases, depending on the capacitance variation according to Q = CV. During the final step of the conversion process, shown in Fig. 2 (c), the generated energy discharges into the storage capacitor, then the variable plate turns back into the initial position.

a)

b)

c)

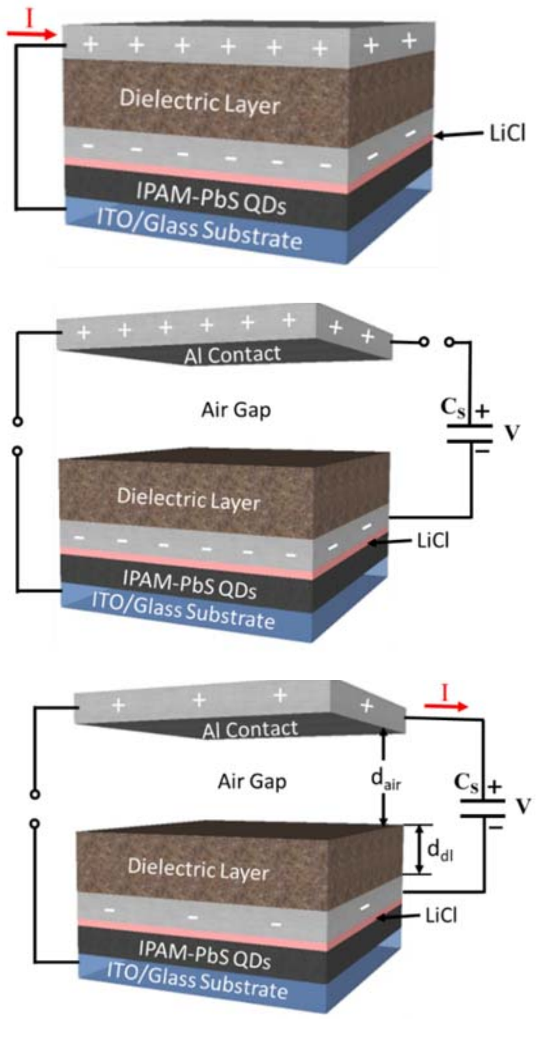

Fig. 2. Working principle of the proposed hybrid energy harvester composed of a photovoltaic device and an electrostatic generator: (a) initial cycle of the energy conversion process where the ITO/Glass contact electrically connected to the movable aluminum and the variable capacitor is charged; (b) movable aluminum contact moving upward and converting the vibration energy into electric energy; (c) final step of the energy conversion process where the variable capacitor discharging into the storage capacitor.

Simulation and Results

The harvested energy per cycle by the proposed hybrid scavenger (both harvested mechanical and thermal energy) is given by:

$$(1) \qquad E_H = E_M + E_{Th} = \left(\frac{C_{max}}{C_{min}} - 1\right) E_0 + E_0 = \left(\frac{C_{max}}{C_{min}}\right) E_0$$

where E_M is the harvested mechanical energy by the electrostatic generator, E_{Th} is the harvested thermal energy by the photovoltaic device, E_0 is the initial polarization energy which equals harvested thermal energy (E_{Th}), and C_{max} and C_{min} are the maximum and minimum capacitance values, respectively. The maximum capacitance value is related to the minimum distance of the electrodes filled with a high permittivity dielectric layer, shown in Fig. 2 (a) and is given by:

$$(2) \qquad C_{max} = C_{di} = \varepsilon_{di}\varepsilon_0 \frac{A}{d_{di}}$$

where C_{di} is the capacitance of the dielectric layer which is oleic acid-capped PbS quantum dots layer, ε_{di} is the relative permittivity of the PbS which equals 169, ε_0 is the permittivity of the free space, A is the overlap area of two electrodes, and d_{di} is the thickness of the dielectric layer. The minimum capacitance value is related to the maximum distance between two electrodes filled with both high permittivity dielectric layer and low permittivity air, as shown in Fig. 2 (b). These two layers are connected in series connections, therefore C_{min} is given by:

$$(3) \qquad C_{min} = \frac{C_{di}C_{air}}{C_{di}+C_{air}} = \varepsilon_{di}\varepsilon_0 \frac{A}{\varepsilon_{di}d_{air}+d_{di}}$$

where C_{air} is the capacitance of the air gap between the upper electrode and dielectric layer, and d_{air} is the thickness of the air gap. In this calculation, parasitic capacitors at edges of the structure are not considered.

Equation (1) shows that the generated energy depends on both the capacitance ratio and the stored energy at the initial step of the conversion cycle, the latter is supplied by the photodetector structure. The initial-stored energy depends on the C_{max} and open circuit voltage of the photovoltaic device. Since the voltage of the photovoltaic device is fix and the decreasing dielectric layer can cause technical issues, capacitance variation is the most common way to improve the generated energy level. Capacitance ratio is given by:

$$(4) \qquad A_C = \frac{C_{max}}{C_{min}} = \varepsilon_{di}\frac{d_{air}}{d_{di}} + 1$$

This equation shows that capacitance variation is significantly affected by the permittivity of the dielectric layer. In particular, incorporating a dielectric layer (double-layer configuration) with high permittivity dramatically improves the energy conversion compared to the conventional single layer electrostatic generators. The presence of high-permittivity dielectric material at the initial step of the conversion cycle results in an increased value of stored initial charges. Besides, the capacitance ratio increases as a result of the high-nonlinear variation of the capacitance as a function of the distance between the two electrodes. Therefore, such an elevated ratio in the capacitance variation and high storage charge in the initial cycle allow a more efficient energy conversion. Capacitance variation for both single-layer structure and double-layer structure is depicted in Fig. 3. In this figure, air (relative permittivity of $\varepsilon_r = 1$) is considered as dielectric for single-layer configuration while the double-layer device includes one additional layer of 1-μm-thick PbS QDs with a relative permittivity of $\varepsilon_r = 169$.

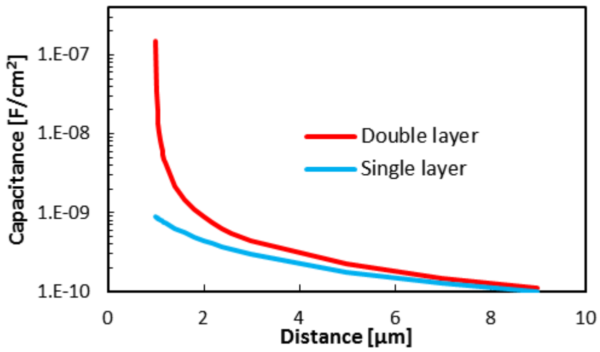

Fig. 3. Capacitance variation versus distance of the electrodes for two configurations.

Harvested energy by the hybrid system is given by equation (1). In this equation, the initial energy, harvested by the photovoltaic device and transferred to the variable capacitance, is given by:

(5) $$E_0 = \frac{1}{2} C_{max} V_0^2$$

where V_0 is the open circuit voltage of the photovoltaic device which equals V_0 = 341 mV [13]. By substituting equation (4) and equation (5) in equation (1) the generated energy as a function of the air gap and dielectric thickness for double-layer configuration is given by:

(6) $$E_H = \frac{1}{2} V_0^2 \varepsilon_0 \varepsilon_{di} \frac{A}{d_{di}} \left(\frac{\varepsilon_{di} d_{air}}{d_{di}} + 1 \right)$$

Fig. 4 depicts the performance of the single-layer and double-layer configurations. Calculated harvested energy density as a function of the gap between two electrodes shows that with 1-mm gap between electrodes single-layer configuration harvests 51.5 nW/cm^2 while the double-layer configuration in the same condition harvests 1.47 mW/cm^2 at vibration frequency of 1 Hz. Double-layer configuration illustrates more than 28,500-fold improvement in the harvested energy over single-layer configuration. In this calculation, start-up voltage equals V_0 = 341 mV. In terms of energy gain, which is equal to C_{max}/C_{min}, the double-layer configuration shows an energy harvesting gain of 168,832 (capacitance decreases from 150 nF/cm^2 at d = 1 µm to 886 fF/cm^2 at d = 1mm) while this number for single-layer configuration is 1,000 (capacitance decreases from 885 pF/cm^2 at d = 1 µm to 885 fF/cm^2 at d = 1mm).

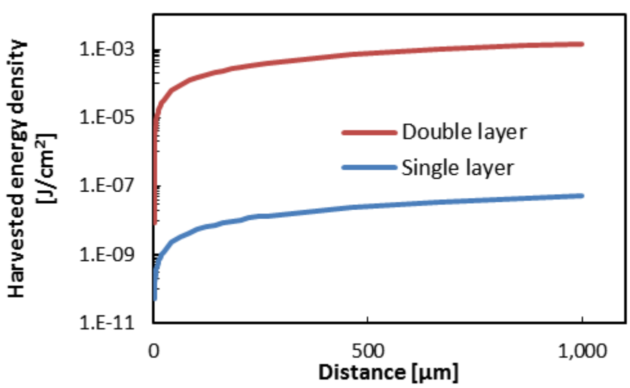

Fig. 4. Calculated harvested energy density versus the distance of the electrodes in single-layer and double-layer configurations. Both structures are supplied with a similar voltage source (V_0 = 341 mV) at the initial state of the conversion cycle.

However, energy loss associated with the charge transfer from energy scavenger to the storage capacitor (C_S) decreases the overall efficiency of the device. This loss depends on both voltage levels and the capacitance of the variable capacitor as well as those of the storage capacitor. Suitable values for voltage level and capacitance can minimize this energy loss.

Fig. 5 shows the equivalent circuit diagram of the device. C_1 denotes the minimum value of the variable capacitor, ready for discharge, while C_S denotes the storage capacitor. V_1 and V_S are the voltages of the C_1 and C_S before connecting the switch. Then, after discharge, the capacitors' voltage is given by:

(7) $$V_2 = \frac{C_1 V_1 + C_S V_S}{C_1 + C_S}$$

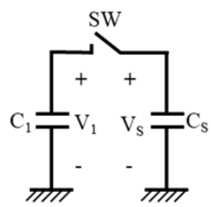

Fig. 5. Equivalent circuit diagram of the energy harvesting device

Accordingly, the energy increment in C_S upon the discharge is given by:

(8) $$\Delta E = \frac{1}{2} C_S V_2^2 - \frac{1}{2} C_S V_S^2 = \frac{1}{2} C_S \left[\left(\frac{C_1 V_1 + C_S V_S}{C_1 + C_S} \right)^2 - {V_S}^2 \right]$$

where ΔE is the energy transferred from harvester to the storage capacitor. This variation is equal to the net generated energy E_H^N. Equation (8) shows that the maximum net energy transfer occurs when $C_S >> C_1$ and

(9) $$V_S = \frac{C_S V_1}{C_1 + 2C_S}.$$

Since $C_S >> C_1$, therefore, approximately $V_S = 0.5V_1$ and $E_H^N = \frac{1}{2} E_H = \frac{1}{4} C_1 V_1^2$.

This calculation shows that maximum half of the generated energy in the energy harvesting device can transfer to the storage capacitor C_S while the storage capacitor is directly connected to the energy scavenger in a parallel configuration. On the other hand, a very large capacitor for C_S can increase the charging time to reach the ideal condition of the $V_S = 0.5V_1$ for optimum operation. Moreover, large capacitance means a large-size capacitor which is not suitable for power harvesting applications. For the simulated double-layer configuration with maximum 1-mm-air gap, energy scavenger requires 70 cycles of operation to charge up the storage capacitor with C_s = 88.6 nF/cm^2 (C_S = 100* C_1) to the optimum operating condition. Moreover, the extractable energy, in this case, is 0.735 mJ/cm^2 which is half the harvested energy (1.47 mJ/cm^2).

Conclusion

This paper presented a simple and efficient hybrid energy scavenger harvesting energy from available thermal and mechanical energy sources of the human body. This device integrates a solution-processed lead sulfide colloidal quantum dot photovoltaic device for harvesting thermal radiation and an electrostatic generator for harvesting mechanical movements. The photovoltaic device provides enough energy to polarize the variable capacitance of the device at the initial step of each conversion cycle and variable capacitance dramatically improves the harvested energy. The thin high permittivity dielectric layer at the variable capacitor magnifies the conversion efficiency of the proposed device by offering high capacitance-variation ratio. Moreover, another important benefit of the high permittivity dielectric layer is providing a smaller inter-electrode distance. This is because of the high breakdown strength; therefore, the device can tolerate higher electric fields, resulting in a significant increase in the stored energy density at the initial step and thus in the overall harvested energy. Theoretical studies show that this hybrid structure improves the conversion efficiency from 2.2 $\mu W/cm^2$ in the case of the harvesting thermal radiation to 1.47 mW/cm^2 by harvesting both thermal and vibration energies of the human body at an operating frequency of 1 Hz. In this structure, oleic acid-capped PbS CQDs are considered as the dielectric layer for the variable capacitor. Moreover, it can be noted that the harvested energy can be improved by increasing the vibration range of the electrodes and by increasing the operating frequency. We also show that at most half the harvested energy can transfer to the storage capacitor device in the presented configuration. The energy transfer efficiency can be improved by incorporating a sophisticated low-consumption circuit.

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