Operation features of electrostatic vibrational energy harvester based on contact potential difference

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Abstract. The paper presents a theoretical study of the electrostatic vibrational energy harvester (e-VEH) operation features based on the work function difference between the variable capacitor electrodes. The analysis was carried out for two types of the conditioning circuits: half-wave rectifier and Bennet doubler circuits both with ideal switches and diodes. Both circuits are able to accumulate electrical energy even for low contact potential differences $V_{bi}$. Bennet doubler demonstrates higher efficiency than the half-wave rectifier. However, when the variable capacitance modulation depth $\eta \geq 2$ it is necessary to introduce special means to limit the voltages growth process and avoid an electrical breakdown for the Bennet doubler circuit. For both circuits with diodes the capacitor voltages become lower than those for the circuits with switches and depend now not purely on the built-in voltage $V_{bi}$ and $\eta$, but also on the used diode parameters. When the values of $V_{bi}$ increase the capacitor voltages for circuits with diodes tend to the corresponding voltages for the circuits with switches. There is also a strong dependence of the capacitor saturation voltage $V_{C1,max}$ on inverse current of the diodes $I_s$. The optimal inverse current of the diodes when the highest saturation voltages are reached is found to be in the range from 50 pA to 100 pA.

1. Introduction

Current achievements in low-power integrated electronics, radio communication, and microelectromechanical systems (MEMS) technology have led to the implementation of integrated sensor nodes operating, as a rule, at a very low power in the range of several microwatts. The combination of a large number of sensor nodes makes it possible to develop wireless sensor networks (WSNs), which are increasingly used in medicine, environmental monitoring, machine health tracking, civil and industrial structures [1]. The main advantages of WSNs: no need of cabling for power supply and data transfer; low cost of system mounting, adjustment and maintenance; hard-to-reach location is possible; reliability and fault tolerance of a whole system.

Most of the wireless sensor nodes are battery dependent. It is well known that batteries need periodical recharging or replacement, that is not always feasible due to the hard-to-reach location of WSN nodes. Therefore, it is desirable for the nodes to be self-powered without conventional batteries. It should be mentioned, that WSN nodes remain in standby mode with low-power consumption for more than 99% of the operation time. Thus, for a typical WSN node with a long duty cycle and low-power consumption, the battery self-discharge rate could exceed the discharge due to the system consumption.

The use of power systems which are capable of getting energy from the environment directly at the place of WSN nodes operation is one of the most attractive alternative to conventional chemical sources.
In addition, the downward trend in energy consumption of modern electronic devices leads to an increase of interest in such kind of power sources.

Electrical energy can be harvested from various sources of environmental energy: sunlight, energy of chemical reactions, electromagnetic and gravitational fields, temperature gradients, fluid and gases flows, kinetic energy because of mechanical vibrations, and energy produced during human activities [2–4]. Due to the ubiquity and availability of mechanical vibrations in environment, the most suitable way of powering remote devices is the use of vibration-to-electrical energy harvesters [5].

There are three main directions of vibrational energy harvesting on the basis of piezoelectric [6], electromagnetic [7] and electrostatic [8] energy converters. Electrostatic (or capacitive) vibrational energy harvesters (e-VEHs) are the most perspective among the others because of their good compatibility to integrated circuit and MEMS processes.

The energy conversion takes place due to external mechanical force work against the attraction force between charged variable capacitor electrodes. In order to maintain the conversion process, the electrostatic principle needs charging of the variable capacitor at all times. This can be realized by charging the capacitor by means of a special electronic circuit [9]. This approach, however, has the disadvantages of a special circuitry which consumes some power itself. Another method of biasing the capacitor is to use electret layers [10], but they have problems concerning long-term stability. The analysis shows that the employment of the variable capacitor based on the use of electrodes with materials having different work functions (WF) can help to provide the initial capacitor charge [11–13].

Nevertheless, under external mechanical vibrations, the e-VEHs will generate ac voltage which cannot be directly used for powering autonomous devices. Thus, it is necessary to have a conditioning circuit which represents some interface between energy harvesting and consuming devices. So far, however, there are not any works devoted to evaluation of operability of such WF vibration-to-electrical energy harvesters along with the conditioning circuits suitable to e-VEHs [14–16], except the resistive load [17]. This paper covers the theoretical analysis of the e-VEH (microgenerator) operation features based on WF difference between the variable capacitor electrodes being connected to the conditioning circuits.

2. Variable capacitor biasing
The energy band diagrams of materials (metals) with different WFs before (a) and after (b) electrical contact are shown in Figure 1. Where \( \phi_1 \) and \( \phi_2 \) are WFs of the materials, while \( E_{F1} \) and \( E_{F2} \) are their Fermi levels. Until the electrodes are joint into a contact, the diagrams are aligned at vacuum level (Figure 1(a)). When the two electrodes are electrically contacted (e.g. by wire connection), the part of electrons will flow from the material with lower WF to the material with higher WF resulting in equilibrium of the Fermi levels (Figure 1(b)) and the emergence of a contact potential difference \( V_{bi} \) between the electrodes.

![Figure 1](attachment:image.png)

**Figure 1.** Energy band diagrams of materials (metals) with different WFs before (a) and after (b) electrical contact

Electrode materials can be combined in accordance with several properties: compatibility between materials, certain parameters of the energy converter (e.g. output power and operating voltage), power capability, etc. It is obvious from the work [18] that to obtain a maximum value of contact potential
difference the following pairs of materials can be applied: $\text{Ni–Mg, } V_{bi} = (1.69–1.38) \ V$; $\text{Au–Mg, } V_{bi} = (1.81–1.44) \ V$; $\text{Pt–Mg, } V_{bi} = (2.27–1.46) \ V$ and $\text{Pt–Al, } V_{bi} = (1.87–0.86) \ V$. Furthermore, these materials can be used in semiconductor technology.

### 3. Study of microgenerator conditioning circuits

One of the most important requirements for electrostatic microgenerator conditioning circuit is a possibility to obtain unipolar stable voltages. Here the authors consider the two most general types of the conditioning circuits at present: half-wave rectifier circuit (circuit 1, Figure 2(a)) and Benet doubler circuit (circuit 2, Figure 2(b)). These circuits are able to work both with switches and diodes. The electrical part of the electrostatic energy converter for both circuits shown in Figure 2 includes a variable capacitor $C_{var}$ and a not physically real voltage source $V_{bi}$, which only indicates the built-in voltage.

![Figure 2](image)

**Figure 2.** Conditioning circuits of the WF microgenerator: (a) – half-wave rectifier circuit (circuit 1), (b) – Benet doubler circuit (circuit 2)

The numerical analysis was carried out using PSpice model with the following parameters: the capacities of the constant capacitors are $C_1 = 1 \ \text{nF}$, $C_2 = 100 \ \text{pF}$, the vibration frequency is $f = 50 \ \text{Hz}$, the built-in voltage $V_{bi}$ was varied from 0.1 to 1.7 V, the time dependence of the variable capacitor capacitance is $C_{var}(t) = C_0[1 - z \cdot \cos(2 \cdot \pi \cdot f \cdot t)]$, where $C_0 = 100 \ \text{pF}$, $z < 1$ is the relative displacement amplitude of the variable capacitor movable electrode. Here the value of $z$ defines the maximal $C_{max} = C_0/(1 - z)$ and minimal $C_{min} = C_0/(1 + z)$ capacities of the variable capacitor $C_{var}$. The maximal-to-minimal capacitance ratio will be referred further as $\eta = C_{max}/C_{min}$.

The normalized time dependences of the storage capacitor $C_1$ voltage calculated for various capacitance modulation depths $\eta$ are shown in Figure 3 for the half-wave rectifier circuit (a) and for the Benet doubler circuit (b) with the switches $S_{wi}$.

![Figure 3](image)

**Figure 3.** Normalized time dependences of the storage capacitor $C_1$ voltage calculated for various capacitance modulation depths: (a) – circuit 1, (b) – circuit 2
It is obvious from Figure 3 that for both circuits, over the time, the normalized storage capacitor \( C_1 \) voltages grow up demonstrating the ability of the system to accumulate electrical energy. Moreover, as the capacitance modulation depth \( \eta \) increases the values of the voltages also increase. However, there are certain differences between these dependences for circuit 1 (Figure 3(a)) and circuit 2 (Figure 3(b)). Firstly, the dependence of the voltages \( V_{C1}(t) \) on \( \eta \) for circuit 1 has a monotonous behavior with a saturation region for all curves, whereas for circuit 2 one can observe a strong dependence of the voltages \( V_{C1}(t) \) on \( \eta \), meaning its higher efficiency for higher \( \eta \) in comparison with circuit 1. Secondly, when \( \eta \geq 2 \), the saturation of the voltages disappears for circuit 2 and an unlimited growth of the circuit capacitors charges and voltages takes place [16], which requires introducing special means to limit the growth process and avoid an electrical breakdown. Theoretical analysis shows that when we use ideal switches the saturation voltage is given by \( V_{C1,\text{max}} = V_{\text{bi}}(\eta - 1) \) for circuit 1, and \( V_{C2,\text{max}} = V_{\text{bi}}(\eta - 1)/(2 - \eta) \) for circuit 2, respectively.

There is no doubt that a conditioning circuit itself should not consume a lot of energy. Thus, it is very important to reduce energy loses because of using electronic switches, which operation has to be synchronized with external mechanical vibration phases. Therefore, diodes are usually used in conditioning circuits as an alternative to the switches. Qualitatively time dependences of the storage capacitor voltage \( V_{C1}(t) \) for circuits 1 and 2 with diodes are similar to corresponding dependences with switches. However, the voltage \( V_{C1} \) values become lower than those for the circuits with switches and depend now not purely on \( V_{\text{bi}} \) and \( \eta \), but also on the used diode characteristics.

Figure 4 shows the normalized dependences of the saturation voltage \( V_{C1,\text{max}} \) on the built-in voltage \( V_{\text{bi}} \) for circuit 1 (Figures 4(a,c)) and circuit 2 (Figures 4(b,d)) with switches \( \text{Sw} \) and diodes \( \text{D} \) having different inverse currents \( I_S \). The capacitance modulation depth \( \eta \) was 1.5 for Figures 4(a,b) and 1.95 for Figures 4(c,d), respectively.

![Figure 4](image-url)

**Figure 4.** Normalized dependences of the saturation voltage \( V_{C1,\text{max}} \) on the built-in voltage \( V_{\text{bi}} \) for circuit 1 (a, c) and circuit 2 (b, d) with switches and diodes at \( \eta = 1.5 \) (a, b) and 1.95 (c, d).
It is clear from Figure 4 that as the value of $V_{bi}$ increases the dependences of the voltage for circuits with diodes tend to the corresponding dependences for the circuits with switches, probably, because when $V_{bi}$ is increased its smaller part drops on the diodes. In addition, there is a strong dependence of the saturation voltage $V_{C1,max}$ on inverse current of the diodes $I_S$, which is especially noticeable for circuit 2, since its performance, for instance, when the built-in voltage $V_{bi} \leq 0.8 \text{ V}$ and $I_S = 1 \text{ nA at } \eta = 1.5$, will be completely impaired. Moreover, as the capacitance modulation depth $\eta$ increases, the requirements for the diodes become less severe.

It was also found that there is an optimal inverse diode current at which the highest saturation voltages are reached. Figure 5 shows the normalized dependences of the saturation voltage on inverse current of the diodes $I_S$ at different values of $V_{bi}$ and $\eta$ for circuits 1 (Figure 5(a)) and 2 (Figure 5(b)), respectively. It is obvious that the optimal inverse current of the diodes is in the range from 50 pA to 100 pA. For diode inverse currents less than 50 pA and more 100 pA the efficiency of the circuits noticeably decreases, especially for currents higher than 500 pA.

![Figure 5. Normalized dependences of the saturation voltage $V_{C1,max}$ on the diodes inverse current $I_S$ at different values of $V_{bi}$ and $\eta$ for circuits 1 (a) and 2 (b), dash lines – $\eta = 1.5$, solid lines – $\eta = 1.95$](image)

4. Conclusion
The theoretical study of the e-VEH operation features based on work function difference between the variable capacitor electrodes was carried out for two types of the conditioning circuits: half-wave rectifier (circuit 1) and Bennet doubler (circuit 2) circuits both with ideal switches and diodes.

It was shown that both circuits are able to accumulate electrical energy even for low contact potential differences $V_{bi}$. It turns out that circuit 2 is more efficient than circuit 1, but when $\eta \geq 2$ it is necessary to introduce special means to limit the voltages growth process and avoid the electrical breakdown across the elements of circuit 2.

The analysis showed that for the circuits with diodes the capacitor voltages become lower than those for the circuits with switches and depend not purely on the built-in voltage $V_{bi}$ and $\eta$, but also on the used diode characteristics. When the value of $V_{bi}$ increases the dependences of the voltage for the circuits with diodes tend to the corresponding dependences for the circuits with switches.

It is necessary to note that there is a strong dependence of the saturation voltage $V_{C1,max}$ on inverse current of the diodes $I_S$, which is especially noticeable for circuit 2. Moreover, as the capacitance modulation depth $\eta$ increases, the requirements for the diodes become less severe.

It was found that there is an optimal inverse diode current at which the highest saturation voltages are reached. The optimal inverse current of the diodes at which the highest saturation voltages are reached is found to be in the range from 50 pA to 100 pA.

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