The electrostatic energy harvesting engineering essay

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this paper presents a general idea of the electrostatic energy harvesting devices. Their working principle, harvesting method and basic designs will be expounded. And another two new approaches, 2D energy harvester and non-resonant energy harvester with rolling mass will be shown. The 2D energy harvester can harvest energy in arbitrary directions in a plane. And non-resonant energy harvester with rolling mass shows its low frequency capability. It can harvest 0. 5 µW at 10Hz. Further improvement of this design may applied to energy harvesting from human body motion.

Introduction

Generally, batteries are the most reliable power source for electronic devices. It is powerful, easy to use. However, it can only provide constant power for a limited period. After that, the batteries have to be changed. Therefore, for those devices that have large amount of number or in inaccessible position. Batteries are not suitable for them. Energy harvesting devices are one of the attractive options of these applications. Energy harvesters can harvest energy from different ambient sources such as solar, thermal and vibration. In these cases, solar is not a reliable source, temperature gradients are modest, vibration seems the more abundant, stable and predictable choices.

Currently, three major methods apply to vibration energy harvesting, electromagnetic, electrostatic and piezoelectric mechanisms. Each technique has its own advantages. Lot of articles did research and provided good conclusion on them. [1-3]

Electrostatic energy harvesting device has the lowest energy harvesting capabilities in these three mechanisms, but it has the most specific advantages. It facilitates CMOS integration [4]. That means it can realize self-power integrated circuits as an on-chip power source. It also environment protects. Unlike piezoelectric and electromagnetic counterparts that require exotic materials. Electrostatic devices are mainly made of silicon.[5]

This paper will focus on the current electrostatic harvesting research. Its working principle and harvesting processes will be discussed in the first part. Some new approaches will also be presented.

electrostatic harvesting

Operating Principle

The electrostatic harvesters harness the work done against the electrostatic force of a variable capacitor. In other words, the vibrations cause the gap distance or overlap area of a parallel plate capacitor to vary under constant charge or voltage condition. This causes the capacitance change of parallel plate capacitor and produces electrical energy.

The fundamental definition is given by the formula below.

$C= Q/V$ (1)

Where C is capacitance of variable capacitor in farads, Q is the charge on the plate in coulombs and V is the voltage on the plates in volts

$C= \varepsilon (A/d)$ (2)

Where A is the overlap area of the plates in and d is the distance between the plates in m. This equation shows the capacitance is proportional to A and inverse proportional to d.

(3)

E is the work done in joules.

If the charge Q is held constant, then V will vary as C changes because of their inverse proportional relationship. Then from, the relation between voltage and capacitor energy is squared rather than linear. As a result, the work done will increase as the C decrease. That provides the harvested energy. Similar thing happens when the voltage V is held constant and Q varies. [1]

They are known as the voltage-constrained method and charge-constrained method. [6] In the recent applications, the charge-constrained method is more popular over the voltage-constrained method as the voltage-constrained method requires an extra charge reservoir to keep the voltage in a constant value, while the charge-constrained method only requires one. [4]

For charge constrained system, as shown in Figure 1 the energy conversion cycle starts as the variable capacitance reaches it maximum Cmax. The charging process is represented by the path from point A to Point B in figure 1. At point B, the energy stored can be shown as,

(4)

From point B to point C, an external charge reservoir is connected in order to keep the charge constant. The capacitance is starting decreasing as the overlap area A decreases or the distance between the plates d increases. The voltage is inverse proportional to the capacitance which is why the voltage increases in this period. This period is the actual mechanical to electrical conversion period. The energy stored at point C is now,

(5)

The path from point C to point A is the discharging of the charge on the variable capacitor back into the charge reservoir

The whole process forms a proper energy conversion cycle. And the amount of energy gain is,

(6)

Usually there is a parallel capacitor is connected parallel with the variable capacitor in order to limit the maximum voltage that might damage the system during the harvesting. Then the energy equation is becoming,

(7)

Figure 1. Charge-constrained energy conversion cycle.

B. Steps of energy harvesting

The vibration cycle in an electrostatic energy harvester has three steps, pre-charge, harvest and reset. Figure 2.

Figure 2. vibration cycle of electrostatic harvester.

In the system, the variable capacitor is pre-charged to the battery voltage, and then the capacitor is connected to the battery. The circuit has no current flow at first since the capacitor and battery have same voltage level. But with the separation of the capacitor plates or the decreases of overlap area, the voltage increases with the decrease of capacitance. Charge therefore flows into the batteries and energy is harvested. When the capacitance reaches minimum value, the energy left in the capacitor will be driven back to the batteries and ready for the next cycle.

C. Basic Designs

These three mechanisms in the figure 3 are the three basic design structures of the electrostatic harvesters, in-plane overlap converter, in-plane gap-closing converter and out-of-plane gap-closing converter. The in-plane overlap converter varies its capacitance by changing the overlap area between comb fingers; the in-plane gap-closing converter varies its capacitance by change the displacement between comb fingers and the out-of-plane gap closing converter varies its capacitance by change the gap between the centre proof mass and two electrode plates.

The most of the current designs of electrostatic harvesters are based on these three basic designs.

Figure 3. (a) in-plane overlap converter. (b) in-plane gap-closing converter. (c) out-of-plane gap closing converter.

D. Comparison in these three designs

Ye Mei Lim[8] did a study on the output energy for these three designs. Firstly the in-plane overlap and in-plane gap closing converters were compared. The Cmax for the one set of comb fingers were 0. 122pF and the Cmin can be treat as zero since the application of silicon nitride dielectric coating which is a very thin layer of chemical (up to 0. 1μm) that can electrically isolate the electrodes even the plates contacts with each other[4]. While using the same set of comb fingers, the Cmax were 0. 149nF and Cmin were 0. 122pF. By applying equation (7), the in-plane overlap converter harvests 1000 times less than in-plane gap closing converter. Then with the simulation of both in-plane gap closing converter and out-of-plane gap closing converter. The results were found out that the in-plane gap closing mechanism is approximately 1. 8 times that of the out-of-plane gap closing mechanism for load volumes between 5 and 50.

NEW APPRAOCHES

A. 2D Electrostatic Harvester

Most of the past electrostatic harvesters are only one degree of freedom. They can only harvest energy via one direction of motion. Y. Zhu fabricates a 2 degree of freedom electrostatic transducer for energy harvesting with resonance frequencies of 38520 Hz and 38725 Hz. It can scavenge energy in arbitrary directions in a plane with two resonance frequency peaks. Also an ultrasound-based method for powering the device is presented.

Y. Zhu’s design includes a 2 degree of freedom motion mechanism. The seismic mass is coupled with both frames as shown in figure 3 with elastic flexures. This design makes the device be able to detect both movements in X and Y frames and also decouples the X and Y movements of the mass.

Figure 4. Two degree of freedom motion mechanism to harvest any direction in-plane vibration energy

Figure 5 shows the SEM image of the 2-DOF electrostatic transducer. And table I are the key parameters of this design. The width difference of X frame and Y frame gives the transducer two different resonance frequencies. The primary resonance frequency at 39238 Hz and second at 39266 Hz. That gives a 302 Hz of -10dB bandwidth. It is twice of the 1D resonator. This device can obtain 10mV through a 1M ohm resistive load and harvest 0. 1 nW power. Since this transducer can be power by an ultrasonic generator of frequency close to its resonance frequency. Since the ultrasonic is relatively safer than other power sources. This design may be useful for functions in medical environment.

Figure 5. SEM image of the 2-DOF electrostatic transducer.

Table 1. key parameter of the 2-DOF energy harvester

B. Non-Resonant electrostatic harvester with rolling mass

M. E. Kiziroglou’s design [10-11] focuses on maximizing the proof mass. In this design, an external free rolling proof mass is introduced. The mechanical energy is proportional to the proof mass, bigger mass generates more energy. This design is a non-resonant device. This property gives it wider applications.

Figure 6. (a) Device structure. (b) Equivalent circuit of the device

The Device structure is shown in figure 6(a). Figure (b) is the equivalent circuit of the device. The stainless steel rod acts as the contact switches and comb finger. When the steel rod is aligned with one of the strip electrodes, it connects with a Cu input Contacts to pre-charge the rod. That generates an electrostatic force between the rod and the strip electrode. That pulls the rod away from the strip electrode and reduces the capacitance at constant charge. The rod then disconnects with the input contact and makes the contact with a discharge electrode. The energy will be transferred as a high voltage pulse. The test of the current prototype of this device reveals a capacitance ratio of 4 and demonstrates a voltage gain of 2. 4.

Later Kiziroglou provides an advanced design of that [12]. This time the glass substrate is form in a cylindrical shape. Figure 7 is fabrication and optical images of the device. The first prototype is characterised with plate size 1 x 10 mm and SiO2 dielectric thickness of 50 nm. A 10 mm-long, 2. 5 mm-diameter steel rod was used. A minimum capacitance of 2 pF and a maximum of 9 pF are observed. The voltage gain is 3 corresponds to a priming voltage 30V. The power generation is 0. 5µW when the rod oscillation frequency at 10 Hz. The biggest advantage of this device is the capability of low frequency. That makes the human body motion as a suitable motion sources for it.

Figure 7. Fabrication and optical images

conclusion

The focus of this paper is to present the general idea current achievement of electrostatic energy harvesting. And it gives a related reference for the group project. For most of the electrostatic harvester designs, a relatively high resonant frequency comparing with human body motion is need. However, the low frequency capability of the non-resonant energy harvester with rolling mass shows the possibility of the application of this technology in the projects. Additionally, most of the current devices only have one degree of freedom. The 2D energy harvester design can harvest arbitrary directions motion in a plane, which sufficiently increases the power output of device. However, it needs a high frequency. That makes it not suitable for the requirement of the project.