Contacting mode operation of work function energy harvester

A Varpula, S J Laakso, T Havia, J Kyynäräinen, M Prunnila
VTT Technical Research Centre of Finland, P. O. Box 1000, 02044 VTT Espoo, Finland
Email: aapo.varpula@vtt.fi, mika.prunnila@vtt.fi

Abstract. The work function energy harvester (WFEH) is a variable capacitance vibration energy harvester where the charging of the capacitor electrodes is driven by the work function difference of the electrode materials. In this work, we investigate operation modes of the WFEH by utilizing a macroscopic parallel plate capacitor with Cu and Al electrodes and varying plate distance. We show that by charging the electrodes of the WFEH by letting the electrode plates touch during the operation a significant output power enhancement can be achieved in comparison to the case where the electrodes are charged and discharged only through a load resistor.

1. Introduction
Electrostatic energy harvesters are based on electrically charged capacitors the capacitance of which is varied by mechanical motion [1–3]. The energy of the mechanical motion is converted into electric energy of the capacitor. The electrostatic energy harvesters need either electret materials or an external power supply, such as battery, for charging of the variable capacitor. This drawback poses challenges in the fabrication and possibly lifetime of these devices. The work-function energy harvester (WFEH) is similar to the electrostatic energy harvester as it utilizes a variable capacitor. However, this energy harvester, illustrated in figure 1, is not dependent on external power supplies or electret materials [4–8]. Instead, the WFEH employs the fundamental difference in the work functions of two dissimilar materials in the charging of the variable capacitor. In this sense the WFEH is closer to a piezoelectric harvester that relies also on the fundamental properties of solid materials. Furthermore, WFEHs can generate more power than the electrostatic harvesters in many operating conditions [8].

The charging effect between two materials with different work functions was thoroughly investigated by Lord Kelvin more than 150 years ago [9, 10], but the use of work function difference in vibration energy harvesting has been, remarkably, proposed only quite recently in 2006 [4]. Since then the work has been concentrated on the modelling and design of WFEHs [5–7]. Comprehensive theory and its comparison with experiments has been performed only very recently in Ref. [8], where, for example, non-contacting operation mode of figure 1c and d was realized with a resistor load. In this work, we extend the experiments of Ref. [8] and realize an operation mode where the WFEH plates touch during the operation cycle. This type of contacting mode of operation can produce an extremely large maximum capacitance which is limited only by the native oxide layers of the capacitor plates, screening length, and parallelism of the electrode plates. As the maximum capacitance defines largely the power output of the WFEH, contacting mode is expected to lead to performance enhancements and, indeed, our experiments show that this operation mode produces significantly more
power than the non-contacting mode. With our macroscopic prototype we obtain a factor of 7.4 power enhancement at 0.5 Hz.

Figure 1. (a,b) Electron energy levels of the electrode materials of the work-function energy harvester (a) before and (b) in the thermodynamical equilibrium after making electrical contact. \(E_{F1}\) and \(E_{F2}\) are the Fermi levels and \(\phi_1\) and \(\phi_2\) the work-functions of the materials 1 and 2, respectively, \(V_{bi}\) is the built-in voltage, and \(e\) is the elementary charge. (c) Charging and (d) discharging phases of the operation cycle of the WFEH. \(u\) is the output voltage. Here a parallel plate WFEH with metal electrodes is illustrated. Semiconductors and other capacitor geometries can be used as well.

In addition to the high maximum capacitance, the benefit of the contacting mode is that it reproduces the key phases of the ideal operating cycle, which produces maximum output power of a WFEH. The contacting ensures that the WFEH capacitor is fully charged before the WFEH begins its work cycle. The drawback of the contacting mode is that energy cannot be harvested from the charging of the WFEH capacitor through the load as the ideal WFEH does. In most cases, however, the energy associated to the through load charging is low \[8\]. Figure 2 shows two circuits exploiting the contacting mode. These circuits have direct application as charge pumps for pumping electric energy into storage capacitors \[8\]. The circuits of figure 2 have the same principle: In figure 2a the charging of the WFEH electrodes is performed using switch S1 and the extraction of the electric energy is controlled using switch S2. In figure 2b the same switching functions are performed by the charge shuttle. The contacting mode corresponds to the case where switch S1 is closed when the electrodes 1 and 2 are in contact and open otherwise. To maximize the power output switch S2 should be closed only when the capacitance of the WFEH is at the minimum. The experiments of this work correspond to the case where switch S2 is constantly closed.

Figure 2. Schematic pictures of work-function energy harvesters based on (a) external switches S1 and S2 and (b) a shuttle. The shuttle and the upper electrode are made of the same material (1) and the lower electrode of material with dissimilar work function (2).

2. Theory
The equilibration of the Fermi levels of the electrode materials of the work-function energy harvester cause electrons to move from the electrode with higher work function to the electrode with lower work function via the circuit connecting the electrodes. In the general case the voltage across the gap between the electrodes of the work-function energy harvester is given by

\[
V_{\text{gap}} = u - V_{bi},
\]  

(1)
where $u$ is the output voltage of the WFEH (i.e., voltage between the WFEH electrodes, measured via the connecting circuit) and the built-in voltage is given by

$$V_{bi} = \frac{\phi_1 - \phi_2}{e},$$

(2)

where $e$ is the elementary charge and $\phi_1$ and $\phi_2$ are the work functions of the electrode materials. In the thermodynamical equilibrium the voltage across the WFEH gap is $V_{bi}$ (see figure 1b). The electric current flowing out of or into the WFEH is given by [8]

$$i = \frac{dQ}{dt} = \frac{d}{dt}(Cu) - V_{bi} \frac{dC}{dt},$$

(3)

where $C = C_{gap} + C_{par}$ is the total capacitance of the WFEH, $C_{gap}$ is the capacitance between the electrodes, and $C_{par}$ is the parasitic capacitance. The $V_{bi} \frac{dC}{dt}$ term is the drive term that leads to non-zero power output of WFEH when $C_{gap}$ is altered by an external force.

Equation (3) is the fundamental equation describing the charging phenomenon caused by the built-in voltage. The overall behaviour of the energy harvester device depends on the external circuit connected to the electrodes. It turns out that the most efficient way to operate the WFEH is to charge or discharge it only when the stored electric energy reaches a maximum or minimum, respectively. These extremes are reached when the WFEH capacitance is at maximum and minimum. This so-called charge constrained operation mode can be realized with an electric switch, for example. The maximum output power of this ideal WFEH produces the average output power of [8]

$$P_{max} = \frac{C_{max}V_{bi}^2}{2\Delta t} \left( 1 - \frac{C_{min}}{C_{max}} \right) \left\{ \frac{C_{max}}{C_{min}} + \frac{C_{min}}{C_{max}} + 2 - \frac{2C_{par}}{C_{min}C_{max}} \left[ 1 + \left( \frac{C_{min}}{C_{max}} \right)^2 \right] \right\},$$

(4)

where $C_{max}$ and $C_{min}$ are the maximum and minimum values of $C$ during the WFEH operating cycle.

3. Experimental

In the experiments the macroscopic prototype of the work-function energy harvester based on variable-distance parallel plate capacitor was employed. The experimental setup is shown in figure 3. 63 mm × 64 mm aluminium and copper plates were used as sample electrode materials. The setup utilizes an electric motor and a gravitational counter force to move the aluminium plate sinusoidally.

**Figure 3.** Schematic pictures of (a) the experimental setup (side view) and (b) the carrier drive system (top view).

In the experiments the electrode plates were connected to a load resistor and an Agilent 4156C precision semiconductor parameter analyzer, which measures the output voltage $u$ (see figure 3a). Prior to experiments the built-in voltage of the Al/Cu system was measured with a null method to be
$V_{bi} = 1.03$ V. The experimental setup is the same as in Ref. [8] and further details can be found there in.

4. Results and discussion

The average output power $P_{max}$ of two ideal WFEHs are plotted in figure 4 as functions of ratio $C_{max}/C_{min}$. The dependence of $P_{max}$ on the built-in voltage $V_{bi}$ and the operating frequency is also shown. These graphs show that high output power can be achieved with high values of $C_{max}/C_{min}$, $V_{bi}$, and the operating frequency. Achieving the high output power suggested by (4) requires that the WFEH is operated similarly as in the ideal case. As discussed above, the contacting operation mode, where the electrodes of the WFEH make periodically electric contact with each other, is close to the ideal operating cycle.

![Figure 4](image-url)

Figure 4. Calculated average ideal power $P_{max}$ of work-function energy harvester as function of $C_{max}/C_{min}$ with (a) $C_{max} = 50$ pF and (b) $C_{max} = 1$ nF and various values of $V_{bi}$ and the operating frequency. Calculated using (4) with $C_{par} = 0$.

Figure 5a and b show the measured output voltages of a WFEH operated conventionally and a WFEH where the electrodes make electric contact with each other once during the operating cycle, respectively. The measured data shows that the peak voltage of the contacting mode WFEH is more than 3 times higher than in the non-contacting WFEH. Both the higher $C_{max}$ and fully efficient WFEH charging contribute to the higher output voltage of the contacting mode WFEH. Since the WFEH is connected to the resistor load at all times, the WFEH capacitor begins to discharge as soon as the contact between the electrodes is lost. On the other hand, this kind of system is also able to harvest energy from the charging of the WFEH electrodes when the electrodes approach each other as can be seen in figure 5b ($t = 0.2 \Delta t...0.4 \Delta t$).

In the non-contacting mode, the optimal operating frequency for maximum power depends on the electric time constant of the WFEH, $RC_{max}$, where $R$ is the resistance of the load [8]. Because of this the average output power of the non-contacting mode, $P_{non-cont}$, shown in figure 5c peaks around 0.2 Hz. Figure 5d confirms that the WFEH with periodic contact between plates produces much higher average output power than the non-contacting WFEH. At 0.5 Hz we obtain factor of 7.4 power enhancement.
(a) Measured time-evolutions of output voltages of the Cu/Al parallel plate work-function energy harvester with a 4 GΩ load resistor at operating frequencies 0.07–0.5 Hz: (a) Operating cycle with the minimum distance between the plates of 200 µm (no contact between the plate surfaces). (b) Case where plates make contact during the operating cycle. Time is normalized with the operating period \( \Delta t \). The amplitude of the sinusoidal motion in both cases is 0.75 mm. The capacitance reaches minimum at \( t = 0 \) and \( t = \Delta t \), and maximum at \( t = \Delta t/2 \). (c) Ratio of measured and ideal average powers, \( P_{\text{non-cont}} \) (case (a)) and \( P_{\text{max}} \). Calculated using (4) with \( C_{\text{par}} = 0.1 \) pF. (d) Ratio of the measured average output powers of cases (b) \( P_{\text{cont}} \) and (a) \( P_{\text{non-cont}} \) as function of the operating frequency of the WFEH.

5. Conclusions
We have demonstrated experimentally the feasibility of the contacting mode work-function energy harvester. A parallel plate WFEH with electrodes contacting each other periodically produced over 7 times higher average output power than the reference WFEH operated without contacting. Our results pave the way towards the realization of the full shuttle-based WFEH. In the microscale these devices could be realized using SiC-based MEMS switching technology [11].

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