Power Generation Characteristics of Single Electrode Output Circuit in Electret Energy Harvester

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Abstract. This paper reports the new output circuit using a single electrode in electret energy harvester, and proves that the single electrode is able to generate output power on grounded load. 3D numerical model of gap-closing type electret energy harvester is presented, and power generation characteristics are analysed and verified. Results show that the two electrodes are actually two independent current sources. Single electrode output circuit has two merits: when only one electrode is connected, it reduces wiring difficulty; when both electrodes are connected to grounded load respectively, it doubles output power compared with traditional output circuit. Using proposed circuit, maximal total power of 30mm×20mm prototype reaches 154.5μW@10Hz, 1.8mm sinusoidal vibration, and an LED has been successfully lighted up.

1. Introduction

Electret energy harvesters have been extensively explored in recent years due to good compatibility with planar processes and relatively higher output power in the low frequency range [1-2]. Latest research concentrates on proposing novel structures with improved output power [3], lowered working frequency [4], or broadened bandwidth [5]. These results prove the potential of electret energy harvesters in applications such as wireless sensor networks, implantable medical devices, and etc.

However, so far in literature most electret energy harvesters utilize the same simple output circuit, which takes the form of load resistors forming a loop with the inherent capacitor of electret energy harvester, as is shown in Fig.1(a). It is typically assumed that current flows from one electrode to another, requiring both electrodes connected to load resistors. Yet this assumption is contradictory to experimental results in [6], as the electret energy harvester with one wiring generates 200μW@20Hz vibration. In fact, little has been investigated about power generation characteristics of output circuit topology, and the mechanism of how the two electrodes function as current source remains unclear.

This paper presents two forms of single electrode output circuit with no loop. Power generation mechanism is theoretically explained and experimentally verified. The two electrodes are tested to be two independent current sources, and novel equivalent circuit is also presented.

2. Single Electrode Output Circuit

In the proposed circuit, “single electrode” can be base electrode (BE) or counter electrode (CE), i.e. only BE or CE is connected to output circuit, as is shown in Fig.1(b) and (c) respectively. Although there is no loop in either topology, power is obtained on grounded load resistances $R_1$ and $R_2$. 

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The principle of single electrode output circuit is in accordance with fundamental electrostatics. In electrostatic equilibrium, induced charges distribute on both BE and CE, and the total amount of induced charges is fixed due to the fixed amount of trapped charges in electrets. This means that increase of induced charges on BE results in decrease of that on CE, and vice versa.

In Fig.1(b), although the distance between trapped charges in electrets and BE remains constant, the electric field between them strengthens (i.e. increased induced charges on BE) as CE vibrates upward (i.e. decreased induced charges on CE), and weakens (i.e. decreased induced charges on BE) as CE vibrates downward (i.e. increased induced charges on CE). As long as load resistors are grounded, changing electric field leads to changing electrostatic equilibrium state, and the flow of induced charges between BE and ground forms the alternating current on load resistors, regardless of whether CE is connected or not. Similar principle also applies for Fig.1(c).

**Fig.1** Output circuit topology: (a) traditional; (b) this work, with only Base Electrode (BE) connected; (c) this work, with only Counter Electrode (CE) connected.

### 3. Theory

A 3D model is adopted to numerically calculate the amount of induced charges on both BE and CE. As is shown in Fig.2(a), assume that electrode width \( w \), electrode length \( l \), position of CE \( g(t) \), electret thickness \( d \) are comparable in dimension. Adopting method of images, trapped charges and image charges are axially symmetrical with respect to electrodes, which is \( \sigma_{\text{img,CE}} \) located at \( z=2g(t)-d \) for CE,

**Fig.2** (a) 3D model of gap-closing type electret energy harvester
(b) Induced charge density on BE when \( g(t)-d=10\mu m \) (upper half) and \( g(t)-d=2\mu m \) (lower half).
and $\sigma_{\text{img,BE}}$ located at $z=-d$ for BE. For simplicity, assume that $\sigma_{\text{img,CE}}$ and $\sigma_{\text{img,BE}}$ are uniform, and neglect electrode thickness and fringing electric field. $\sigma$ represents trapped charge density of electrets, $\varepsilon_r$ relative dielectric constant of electrets, and $\varepsilon_0$ vacuum permittivity.

Based on fundamental electrostatics, induced charge density of BE $\sigma_{\text{BE}}$, and that of CE $\sigma_{\text{CE}}$ are:

$$\sigma_{\text{BE}}(z) = \varepsilon_r\varepsilon_0 E_{\text{BE}}(z) = -\varepsilon_r\varepsilon_0 \frac{\partial \varphi_1(z)}{\partial z}, \quad \sigma_{\text{CE}}(z) = \varepsilon_r\varepsilon_0 E_{\text{CE}}(z) = -\varepsilon_r\varepsilon_0 \frac{\partial \varphi_2(z)}{\partial z}$$

(1-1, 1-2)

where $\varphi_1(z)$ and $\varphi_2(z)$ are potential functions in Region 1 and Region 2. Due to dielectric discontinuity between two electrodes, $\varphi_1(z)$ and $\varphi_2(z)$ are solved separately, both using superposition theorem:

$$\varphi_1(z) = \frac{1}{\varepsilon_r} \left( \varphi_{\text{elct}}(z) + \varphi_{\text{img,BE,1}}(z) + \varphi_{\text{img,CE,1}}(z) \right), \quad \varphi_2(z) = \varphi_{\text{elct}}(z) + \varphi_{\text{img,BE,2}}(z) + \varphi_{\text{img,CE,2}}(z)$$

(2-1, 2-2)

In Eq.(2-1)~(2-2), potential function caused by electrets $\varphi_{\text{elct}}(z)$, by image charges on BE $\varphi_{\text{img,BE}}(z)$, and by image charges on CE $\varphi_{\text{img,CE}}(z)$ are derived by integrating potential from charge per area:

$$\varphi_{\text{elct}}(z) = \int_1^\infty \int_1^\infty \int_1^\infty \frac{-\sigma_{\text{BE}} \, dx \, dy \, dz}{4\pi\varepsilon_0 \sqrt{(x-x_0)^2 + (y-y_0)^2 + (z-d)^2}}$$

(3)

$$\varphi_{\text{img,BE},i}(z) = \int_1^\infty \int_1^\infty \int_1^\infty \frac{\sigma_{\text{BE},i} \, dx \, dy \, dz}{4\pi\varepsilon_0 \sqrt{(x-x_0)^2 + (y-y_0)^2 + (z+d)^2}}$$

(4)

$$\varphi_{\text{img,CE},i}(z) = \int_1^\infty \int_1^\infty \int_1^\infty \frac{\sigma_{\text{CE},i} \, dx \, dy \, dz}{4\pi\varepsilon_0 \sqrt{(x-x_0)^2 + (y-y_0)^2 + (z-2g(t)+d)^2}}$$

(5)

where $i=1$ or 2, $\sigma_{\text{BE},i}$ is $\sigma_{\text{img,BE}}$ for solution in Region $i$, and $\sigma_{\text{CE},i}$ is $\sigma_{\text{img,CE}}$ for solution in Region $i$.

Substituting potential functions $\varphi_1(z)$ and $\varphi_2(z)$ to interface continuity equations and zero potential boundary conditions solve $\sigma_{\text{BE},i}$ and $\sigma_{\text{CE},i}$, and further substituting $\sigma_{\text{BE},i}$ and $\sigma_{\text{CE},i}$ to Eq.(1-1)~(1-2) renders the numerical results for $\sigma_{\text{BE}}$ and $\sigma_{\text{CE}}$. Fig.2(b) shows the numerically obtained $\sigma_{\text{BE}}$, which is in accordance with previous analysis that induced charges on BE increase as gap between BE and CE increases, and vice versa. Similar numerical results can be obtained for $\sigma_{\text{CE}}$.

Based on these, BE and CE are modeled as two separate current sources independently generating current, as is shown in Fig.3. $i_{\text{BE}}$ and $i_{\text{CE}}$ are total current of BE and CE, which is proportional to $v_{\text{vib}}$, vibration velocity of CE, as is shown in Eq.(6)~(7). $C_{\text{BEG}}$ and $C_{\text{CEG}}$ are ground capacitance parallel to grounded load. The two current sources can work individually or simultaneously.

![Fig.3 Equivalent circuit of gap-closing type electret energy harvester.](image)

\[ i_{\text{BE}}(t) = -\frac{dQ_{\text{BE}}(t)}{dt} = -\frac{\sigma_{\text{BE}}(g(t))h \omega}{d(g(t))} \frac{d(g(t))}{dt} = -\frac{\sigma_{\text{BE}}(g(t))h \omega}{d(g(t))} \cdot v_{\text{vib}} \]

(6)

\[ i_{\text{CE}}(t) = -\frac{dQ_{\text{CE}}(t)}{dt} = -\frac{\sigma_{\text{CE}}(g(t))h \omega}{d(g(t))} \frac{d(g(t))}{dt} = -\frac{\sigma_{\text{CE}}(g(t))h \omega}{d(g(t))} \cdot v_{\text{vib}} \]

(7)

Power on load resistors is as follows:

\[ P_{\text{BE}} = \frac{i_{\text{BE}}(t)^2 R_{\text{BE}}}{1 + j \omega C_{\text{BEG}} R_{\text{BE}}} \]

\[ P_{\text{CE}} = \frac{i_{\text{CE}}(t)^2 R_{\text{CE}}}{1 + j \omega C_{\text{CEG}} R_{\text{CE}}} \]

(8-1, 8-2)
4. Experimental Verification

Fig. 4 shows the experimental setup for verifying the proposed circuit. The upper slider of the linear ball guide is fixed, while the lower slider is driven by electromagnetic shaker. PMMA fixtures are fixed on the two sliders for clamping BE and CE. BE with electrets (area: 30mm×20mm, surface potential: -700V) is fixed on the upper slider, and CE vibrates up and down with the lower slider, thus forming a gap-closing type electret energy harvester. The displacement of CE is recorded by an eddy current sensor. During test, $R_1$ is variable from 10M$\Omega$ to 500M$\Omega$, while $R_2$ is fixed 1M$\Omega$ to minimize the influence of probe resistance. The entire setup is effectively grounded to minimize EMI effects.

When only BE/CE is connected, measured voltage is shown in Fig.5(a) and (b), respectively. Voltage waveforms of BE and CE are in opposite phase. This is in accordance with electrostatic induction principle, since charge increases on BE implies that charge decreases on CE. Maximum BE/CE voltage occurs slightly before/after maximum CE displacement due to small gap and high vibration velocity. These results prove the power generation capability using single electrode output circuit, and exclude the possibility of displacement current.

Fig. 6 displays the characterization results of output voltage. In Fig.6(a), BE/CE voltage decreases as gap between BE and CE increases. In Fig.6(b), BE/CE voltage increases as vibration frequency increases. These results agree well with theoretical analysis of gap-closing type electret energy harvester, thus proving measured voltage and power is indeed generated by electret energy harvester. Since voltage of BE or CE is almost the same, in practice connecting either electrode generates almost equal power. This greatly reduces wiring difficulty, for instance the vibrating CE can be floated while power is generated from the fixed BE.

When BE and CE are respectively connected to grounded load, the total power doubles that of the traditional output circuit in Fig.1(a). As is shown in Fig.7, as BE and CE are respectively connected to
110MΩ grounded load resistance (i.e. total resistance is 220MΩ), maximal total power reaches 154.5μW@10Hz, 1.8mm sinusoidal vibration. This is two times of the maximal power using traditional output circuit, which is 74.9μW on 110MΩ under the same vibration condition. Therefore, single electrode output circuit also helps to double output power by utilizing generation capability of both electrodes.

Fig.8 shows photos of using single electrode output circuit to power a light emitting diode (LED). BE (or CE) is solely connected to Schottky rectifier bridge to convert AC voltage of harvester into DC voltage, and generated power is stored in 47μF capacitor. The LED is dim when there is no vibration, and is light under 100Hz, 0.5mm sinusoidal vibration, as is shown in Fig.8(a) and (b), respectively. These results further solidify the applicability of proposed single electrode output circuit.

**Fig.8** Photos of LED application using only BE/CE for output: (a) dim LED under no vibrations; (b) light LED under 100Hz, 0.5mm sinusoidal vibration.

**Conclusion**
This paper reports the new output circuit using a single electrode in electret energy harvester, and proves that the single electrode is able to generate output power on grounded load. 3D numerical model of gap-closing type electret energy harvester is presented, and novel equivalent circuit is presented. The two electrodes are tested to be two independent current sources, and the experimental power generation characteristics agree well with theoretical analysis. Single electrode output circuit reduces wiring difficulty when only one electrode is used, and doubles output power compared with traditional circuit when two electrodes are respectively connected to grounded load. Using the proposed circuit, for the 30mm×20mm prototype, maximal total power reaches 154.5μW@10Hz, 1.8mm sinusoidal vibration, and an LED has been successfully lighted up.

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