A Frequency-Independent Vibrational Energy Harvester using Symmetrically Charged Comb-Drive Electrodes with Heavily Doped Ion Electrets

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Abstract. An energy harvester has been developed to efficiently earn energy from both cyclic and impulse vibrations by using a symmetric pair of comb-electrodes that are heavily doped with potassium-ions to form electrets. By equalizing the electromechanical forces on the opposing comb-drives, energy conversion efficiency is enhanced for both impulses and broad-frequency harmonic vibrations.

1. Introduction
Energy harvesting is a vital component for Internet-of-Things (IoT) [1] sensing nodes that must operate without batteries. In such applications, batteries are not an appropriate power source because they must be frequently replaced. Typically, more than 1 mW is necessary as a power source for both sensors and wireless radio transmission devices. In order to generate large power, most existing devices are optimized in two ways; first type uses large electrostatic charges coupled with movable electrodes and the other type has a large resonant response, in harmonic terms a high Q-factor, at a selected frequency. However, these devices are ill-suited to capture energy from ambient vibrations such as human and vehicular motion which consist of random vibrational patterns and incoherent impulse rather than consistent harmonic vibrations. This deficiency arises because large electrical charges cause strong electrostatic attraction and tend to make the devices too stiff to respond to weak vibration. Furthermore, such devices are incapable of capturing wide spectrum vibrational energy from random and incoherent impulses due to a narrow resonant frequency peak represented by a high Q-factor. Therefore, these devices can only respond to either large amplitude impulse motions or consistent harmonic motions within a specific frequency range. We have developed a device that overcomes these limitations.

From amongst three major types of vibrational energy harvesters (i.e., piezoelectric, electromagnetic, and electrostatic) for distributed sensor network nodes, we used the electrostatic type based on potassium-ion electrets because of the compatibility with impulse and broad-frequency harmonic vibrations. Compared to electrets made by corona discharge [2] or soft X-ray radiation [3], electrically
activated solid ions in potassium-doped silicon dioxide can generate extremely strong electric fields even within the narrow gaps of a comb-drive [4]. In this work, we propose a novel device to achieve high efficiency energy conversion for both impulse and broad-frequency harmonic vibrations.

2. Concept and Device

2.1. Power generation method

Developed energy harvester shown in Figure 1, and the device uses symmetrically arranged comb-drives electrodes with charged electrets coupled with a moveable electrode mass. By using an electrically symmetrical configuration, the additional rigidity that usually arises from electrostatic attraction can be balanced and cancelled, thereby keeping the mechanical stiffness of the device independently from the electret bias voltage.

When the packaged device is mechanically shaken by an amount of $Y$ from external vibration, the moveable mass inside the energy harvester chip is displaced by $X$. This motion can be described by equation (1.1). As shown in Figure 1 voltages $V_L$ and $V_R$ are generated at the left and right comb-drives, respectively, as a result of this motion. Consequently, the output current $I$ (1.3) flows through the load resistor $R$. As can be seen in the expression for Q-factor (1.4), a large force factor $A$, achieved by applying a large electret voltage $V_0$ between the narrow gap $g$ of the comb-drive (1.2), can reduce the Q-factor. The low Q-factor allows the device to freely capture low-amplitude impulse vibrations as well as wide-frequency harmonic motions by the efficient and fast conversion of the kinetic energy of the mass to electrical energy.
2.2. Fabrication and Device
The energy harvester device shown in Figure 2 was fabricated by using double-sided Deep-RIE processes on an SOI wafer. The chip (8 mm × 13 mm) consisted of symmetrical pairs comb-drive-electrodes on both sides of the mass. The whole device was thermally oxidized at 980°C with an aqueous KOH bubbler to form the ion-rich silicon dioxide film. In order to prevent the oxidization of the electrical contacts, the area where contact pads were fabricated was covered with a 100-nm-thick silicon-nitride (Si₃N₄) film by low-pressure chemical vapor deposition (LPCVD) before the oxidation process. Finally, the potassium-doped-oxide was electrically polarized at approximately 500°C by applying a 150-V bias voltage for approximately 15 minutes to form a built-in electret with a large static charge.

2.3. Electret characteristics
In order to measure the electret charging voltage, we adopted the experimental setup shown in Figure 3(a). We measured the current passing through the left electrode, by sensing the motion of the mass induced by AC excitation by 0.2 V at 1 kHz, while applying a voltage to the right side in order to gradually neutralize the static charge on that side only. We then repeated the experiment after exchanging the right and left side. As can be seen in Figure 3(b) and (c), the both sides exhibited the same displacement dependence on DC bias, indicating that the two electrets are equally biased at 150 V.

3. Experimental & Simulation

3.1. Experimental setup and Results
Figure 4(a) shows the experimental setup. We performed a proof-of-concept experiment to demonstrate the electrical characteristics of the device by actuating the unpackaged harvester using a probe station. In Figure 4(b), the vertical axis represents the mechanical energy stored within the device after a manual impulse was applied to the device. In the top graph of Figure 4(b), the device was not connected to a load resistance, and therefore did not lose a significant amount of energy over time. When a 10 MΩ load was connected in the bottom graph of Figure 4(b), however, the full impulse energy was transmitted to the electrical load within less than two seconds. In other words, large electrical damping is introduced to the oscillator in a form of energy transmission to the load resistance.

3.2. Simulated Results and Discussion
Figure 5 shows the simulated output of two devices with electrets of different voltages. The output has been normalized to the applied acceleration required to displace the mass by 200 µm. As can be seen, the higher the electret voltage is, the lower the Q-factor, thereby allowing to efficiently harvest the energy across a wide frequency range. Moreover, this small Q-factor also enables the rapid decay of vibrations caused by energy conversion. It is ideal for capturing successive impulse vibrations.

4. Conclusion
In this study, we have proposed an energy harvester by using symmetrically charged comb-drive electrodes featuring very low Q-factor owing to the extremely high force factor A based on our potassium-ion-electret. The proposed technology allows us to achieve high efficiency energy conversion for both impulse and broad-frequency harmonic vibrations that are abundant around us.

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