Study of Electrostatic-induced Energy Harvester Using Ferroelectric Dipole Electret

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論文内容要約

Recently, there is growing interest in autonomous wireless sensor networks aiming at automated health monitoring of vehicles, facilities, buildings, infrastructures, and humans. One of the key issues is to develop a maintenance-free power source for operating sensor nodes composing the autonomous wireless sensor networks. An electrostatic vibration energy harvester using a charged dielectric termed "electret" is being recognized as a promising solution since it can convert low-level mechanical vibration available in ambient environment (typical frequency and acceleration are below 200 Hz and 9.8 m/s^2, respectively) into electricity. However, its output power still remains low, compared to other transduction such as electromagnetic or piezoelectric. Furthermore, as well as higher output power, vibration energy harvesters desperately require wider operational frequency band in order to scavenge energy even when the peak frequency of ambient vibration moves out of their resonance frequency. Main theme of this work is to develop a high performance electret-based out-of-plane vibration energy harvester with high output power as well as wide frequency band.

To significantly enhance output power of electrostatic vibration energy harvester above that obtained from conventional polymer- or silicon-based electrets, this study proposes an electret utilizing dipole orientation of ferroelectric material, termed ferroelectric dipole electrets (FDEs), and establishes a method of extracting substantial electric field outside the FDE. After poling treatment, a poled ferroelectric material function as an FDE, by removing the electrodes and thus the electric double layers formed at the interface between the electrodes and the poled ferroelectric material. Then, I theoretically investigated net electric field outside the FDE using a parallel plate capacitor model, and revealed that the net electric field outside the FDE enhances not only higher surface charge density but also greater thickness of the FDE. According to the theoretical prediction, the resulting output powers of FDE-based out-of-plane vibration energy harvester were enhanced with increasing the surface charge density and thickness of the FDEs. The output power density for the FDE developed in this study was 78 μW/cm^3, a three-fold increase over a conventional polymer electret. I expect that FDE would accomplish further enhancement in output power if we could establish a way of improving incomplete polarization of the FDE due to currently-employed poor electrical

contact between the PZT ceramic and the copper foil tape electrode.

The newly-developed electret termed FDE exhibited instability of surface potential, whereas it can afford significant enhancement in output power. This study proposes two possible mechanisms of the surface potential instability of the FDEs, "the depoling" and "the space charge screening," and determined which of the mechanisms triggers the instability of the FDE. The FDEs were prepared from hard type PZT ceramics against the depoling and from PMN-PT single crystal against the space charge screening. This study found in experiment that the origin of the instability of FDE is attributed to the depoling not the space charge screening, and the FDE formed from hard type PZT ceramic exhibits longer surface potential stability as well as higher output power, compared to the other FDEs formed from soft type or from single crystalline ferroelectrics. Moreover, the hard FDE at higher level of polarization by applying higher poling voltage showed longer stability. Therefore, the hard type ferroelectric material and the enhancement in its polarization level are promising for extending life time of FDEs.

To further enhance output power of an FDE-based out-of-plane vibration energy harvester, we also need to develop a robust oscillator that can travel without fracture under 0.1-1 mm displacement. Under such large displacement, a silicon-based oscillator widely employed in MEMS sensors is not appropriate in terms of mechanical reliability, even with the advantage of high-precision processing. We should find an alternative material with higher mechanical reliability as well as applicability to high-precision processing. As a promising material for such an oscillator, this study proposes a fine-grained stainless steel film with the smaller grain size and the improvement of adhesion to photoresist. The oscillator fabricated from the fine-grained stainless steel showed smooth edges, less side-etched depth, and larger taper angles compared to the oscillator from typical stainless steel.

To achieve wider frequency band of an electret-based out-of-plane vibration energy harvester, I investigated the dependence of harvester's performance (output power, resonance frequency, and frequency band width) on the initial air gaps, both numerically and experimentally. With reducing the initial air gap, enhanced electrostatic-force induced soft spring effect, by which wider frequency band and lower resonance frequency are achieved, whereas output power has peak value at a certain initial air gap. Reducing the initial air gap is a promising scheme for wide frequency band in out-of-plane vibration energy harvester.

Finally, based on the results above described, I have developed a high performance electret-based out-of-plane vibration energy harvester by combining the FDEs and the fine-grained stainless steel-based oscillator. In practical use, a strong attractive electrostatic force of the FDE can easily cause a pull-in effect, by which an oscillator snaps and sticks to the FDE. To prevent the pull-in, this study proposes a non-linear spring with stopper. The FEM analysis validated that the proposed non-linear spring can withstand the expected pull-in force of the FDE by increasing the spring constant after the contact with the stoppers. The FDE-based out-of-plane vibration energy harvester showed no pull-in, and maximum raw output power of 27 μW and frequency band width 19 Hz at applied acceleration 9.8 m/s^2. The maximum output power for the FDE at applied acceleration 9.8 m/s^2 showed a 1.6-fold increase over the conventional polymer electret. In comparison to the state-of-the-art, the developed harvester achieved wide frequency band, as well as the highest normalized power density.