A Silicon Disk with Sandwiched Piezoelectric Springs for Ultra-low Frequency Energy Harvesting

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Abstract. Exploiting the sporadic availability of energy by energy harvesting devices is an attractive solution to power wireless sensor nodes and many other distributed modules for much longer operation duration and much lower maintenance cost after they are deployed. MEMS energy harvesting devices exhibit unique advantageous of super-compact size, mass productivity, and easy-integration with sensors, actuators and other integrated circuits. However, MEMS vibration energy harvesting devices are rather difficult to be used practically due to their poor response to most of the ambient vibrations at ultra-low frequency range. In this paper, a micromachined silicon disk with sandwiched piezoelectric springs was successfully developed with resonant frequency of 15.36~42.42 Hz and quality factor of 39~55 for energy harvesting. Footprint size of the device was 6 mm × 6 mm, which is less than half of the piezoelectric cantilevers, while the device can scavenge reasonably high power of 0.57 μW at the acceleration of 0.1 g. The evaluation results also suggested that the device was quite sensitive as a sensor for selective monitoring of vibrations at a certain frequency.

1. Introduction
In recent years, the rapid market growth, along with many great challenges, in Internet-of-Things (IoT), wearable healthcare and medical devices, industrial 4.0, and wireless sensor networks (WSN) is becoming one of the major drivers for the R&D of innovative semiconductor devices, various MEMS sensors and actuators, as well as integration techniques [1][2]. The ubiquitous applications of above system may require thousands of sensor nodes, actuators, or other modules to be deployed arbitrarily and operate autonomously for collecting enough data in real-time, cooperatively pass their data through network to a main location, and then execute instruction efficiently. Among the challenges to be coped with, power source to each sensor nodes, actuators, or modules is most essential for high system flexibility and low maintenance cost [3]. The research on power source may create huge new opportunities for manufacturers in near future.

Compared to many other alternative power sources such as thin-film and printed batteries, small flexible photovoltaics panels and thermoelectric modules, MEMS energy harvesting devices [4]-[6] exhibit unique advantageous of super-compact size, mass productivity, and easy-integration with sensors, actuators, and other integrated circuits. Especially to piezoelectric lead zirconate titanate
(PZT) cantilever, although the application fields so far mainly focused on low power devices, it still remains in critical area of interest due to its excellent electrical-mechanical conversion coefficient [7]. PZT cantilever is also believed promising as a self-powered sensor for selectively monitor of vibrations from a machine or infrastructures, if the cantilever is well designed for a certain target frequency [8]. However, since most of the ambient vibrations occur in ultra-low frequency range, i.e. 1-20 Hz for human and animals, <100 Hz for machines, it is rather difficult to obtain an enough high power density and device output from ambient vibrations by PZT cantilever for its poor responses. Increase cantilever’s footprint size of up to 1 cm × 1 cm may dramatically reduce its resonant frequency to less than 30 Hz [9-11], but at the cost of process expenses and integration difficulties.

In this paper, a micromachined silicon disk with piezoelectric springs was successfully developed with ultra-low resonant frequency of 15.36~42.42 Hz and quality factor (Q-factor) of 39~55. The dependence of resonant frequencies, Q-factor, and initial deformation on device structure was investigated both theoretically and experimentally. The results reveal that the device can scavenge reasonably high power of 0.57 μW at the acceleration of 0.1 g, while footprint size of the device was less than half of most piezoelectric cantilevers. Moreover, the potential applications of above devices for not only energy harvester but also self-powered vibration sensor were investigated and discussed herein.

2. Experimental

2.1. Device design and fabrication

Fig. 1 shows SEM image of the device. A silicon disk, which is supported by 3 springs symmetrically, was designed as the proof mass with the thickness of up to 400 μm. Sandwiched piezoelectric PZT thin film was fabricated on the springs to harvest energies when the disk was actuated along the out-of-plane direction. The PZT thin film can be also used as self-powered sensing elements to monitor vibrations of a machine or infrastructure. For the pursuit of low resonant frequency, finite elements analysis (FEA) was carried out, and then thickness of the spring and the PZT film was set at 3 μm and 1.9 μm, respectively. Width of the springs was 100 μm or 200 μm, and diameter of the disk was 2 mm, 2.5 mm, or 3 mm to investigate their performances at different resonant frequencies.

Fig. 2 shows flowchart of the fabrication process, which was started by using silicon in insulator (SOI)
wafer with a 3 µm-thick active silicon layer. The PZT and its electrodes were first deposited on the SOI wafer by sol-gel process and sputter, respectively (fig.2 (a)). Then, the PZT and the electrodes were patterned by wet etching and dry etching in turn (fig.2 (b)), followed by inductively coupled plasma reactive ion etching (ICP-RIE) (MUC-21, Surface Technology System Co., Ltd) of active silicon layer and reactive ion etching (RIE) (RIE-10NRS, SAMCO Co., Ltd) of SiO₂ box layer (fig.2 (c)) to create the springs. Finally, the silicon disk was released from backside of the wafer by ICP-RIE.

2.2. Device evaluation
The initial deformation of the device was measured by using a high-precision non-contact depth measuring microscope (DH2-150, UNION Optical Co., Ltd). Then, the device was set on an air-isolated anti-vibration table to avoid any effects from ambient environment. A program controllable mechanical shaker was used for device actuation at a certain frequency and acceleration. Configurations and photo of the evaluation system was shown in Fig. 3. Laser Doppler velocimetry (LDV) (LT7901, Graphtec Co.) was used to evaluate resonant frequencies and $Q$-factor of the device. Electrical output current and voltage of the device was measured by a controller equipped with 24-bits AD convertor.

3. Results and Discussion
The resonant peaks of the device with 100 µm-wide PZT springs and different disk diameters were summarized in Fig. 4 for comparisons. It can be found that ultra-low resonant frequency of 15.36 Hz, which was believed by the disk vibration in out-of-plane direction, was obtained when the disk diameter was 3 mm. $Q$-factor of the disk was calculated as 39, indicating that except for energy harvesting, the device was quite sensitive for the monitoring of vibrations with frequency of less than 20 Hz. In the calculation, $Q$-factor was defined as the ratio of the cantilever resonant frequency to the bandwidth of the resonant peak at -3 dB power.

Fig. 4 also reveals that when the disk diameter was 2.5 mm and 2 mm, resonant frequency of the device was slightly increased to 21.70 Hz and 34.11 Hz, respectively. $Q$-factor of the devices was then increased from 39 to 55 with the decrease of disk diameter. As shown in Fig. 5, the device with 200 µm-wide PZT springs shows very close performances with resonant frequency of 19.0 Hz, 27.19 Hz, and 42.42 Hz when disk diameter was 3 mm, 2.5 mm and 2 mm. $Q$-factor of the devices was increased from 41 to 54 with the decrease of disk diameter. Clearly, the developed device exhibits mechanical characteristics similar to other piezoelectric energy harvesters, but the footprint size was less than half of PZT cantilevers [11] and the volume was less than 10 % of the piezoelectric ceramics [12]. Those issues are favourable for manufacturers to reduce production cost.
Figure 4. Measured device responses at different frequencies and disk diameters. The width of the piezoelectric spring was 100 μm.

Figure 5. Measured device responses at different frequencies and disk diameters. The width of the piezoelectric spring was 200 μm.

It worth noticing that resonant peak at around 50 Hz can be found from all the devices in both Fig. 4 and Fig. 5. It is believed due to the resonant frequency of the anti-vibration desk. Besides, sub-peaks can be observed in the device with disk diameter of 2 mm, probably due to ‘in-plane’ vibration because ‘smaller’ disk is more ‘un-stable’ by actuation. Although corresponding resonant frequency of those sub-peaks was a bit high (60 Hz when spring width was 100 μm; 90 Hz when spring width was 200 μm), it might be an promising solution to ‘flatten’ the resonant peak with lower $Q$-factor for better energy harvesting from ambient vibrations.

### Table 1. Summery of the measured mechanical properties of the devices.

| Disk Diameter (mm) | 2   | 2.5 | 3   |
|-------------------|-----|-----|-----|
| Spring Width (μm) | 100 | 200 | 100 | 200 |
| Resonant Frequency (Hz) | 34.11 | 42.42 | 21.70 | 27.19 | 15.36 | 19.00 |
| $Q$-factor        | 55  | 54  | 46  | 50  | 39  | 41  |
| Initial Deformation (μm) | 208 | 175 | 640 | 413 | 1525 | 688 |

Most of the device suffers from package difficulties and reliability because of the proof mass [11] [13]. As shown in Table 1, initial deformation of the disk was a bit large when disk diameter was 3 mm, but it is acceptable if the ratio of disk size to initial deformation is considered. Table 1 also indicated that the initial deformation can be dramatically reduced by increasing of the spring width or decreasing of the disk diameter, but at the cost of higher resonant frequencies. By applying residual stress in sandwiched PZT springs may greatly reduce the device initial deformation as well as to improve performance of the device. Moreover, it is believed that many other piezoelectric thin films, i.e. aluminium nitride (AlN), can be used as the energy harvesting or sensing elements for a better process compatibility and process flexibility. These works are undergoing and the results will be presented in our future publications.
Fig. 6 shows measured electrical output from the sensor when the acceleration was 0.1 g. The peak power was calculated as 0.57 µW, close to that of PZT cantilever [11]. The output power is expected can be further improved by higher acceleration of up to 0.2–0.3 g, which exists in most of the machines, infrastructures, as well as ambient environments. Fig. 6 also suggested that this device may selective response to a certain frequency, not only as an energy harvester but also as a vibration sensor.

4. Conclusions
In this paper, we have presented a silicon disk with PZT springs for energy harvesting applications. The results demonstrated that ultra-low resonant frequency of < 20 Hz and reasonably high power output of > 0.5 µW can be achieved by the device with footprint size of 6 mm × 6 mm. Further research and device optimization will enable the practical applications of this device in IoT, WSN, etc.

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Figure 6. Measured voltage and current output of the device with disk diameter of 3 mm and spring width of 200 µm, when the acceleration was 0.1 g. The peak power was calculated as 0.57 µW.