A Novel Piezoelectric Microgenerator with Wide-Bandwidth Vibration Energy Harvesting Based on Optimal FOM Design

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Abstract

This paper presents a novel micromechanined piezoelectric generator harvesting mechanical energy in a wide vibration bandwidth. Based on optimal Figure of Merit (FOM) and our developed scheme, the size of 3mm x 3mm x 5mm generator is composed of four connected-in-parallel cantilever structures, which are fabricated by an innovative process with the advantages of flexible membrane and minimized residual stress to achieve a large displacement. The designed generator is targeted at producing the power of microwatt to milliwatt in a reasonable wide mechanical vibration range (e.g. 300-800 Hz).

Keywords: Piezoelectric, Bandwidth, Vibration, Figure of Merit (FOM)

1 - INTRODUCTION

Recently increasing focus on the development of networks of wireless sensor nodes has been found in many literatures. Applications for ubiquitous wireless sensor networks range from environmental monitoring and control of industrial buildings to military and aerospace fields. Meanwhile, Advanced in low power VLSI design and CMOS fabrication have reduced power requirements for wireless sensor nodes. Therefore, self-powered nodes is not only a dream [1].

To realize the self-powered wireless sensor network technology, efficient energy scavenging becomes crucial. For numerous energy sources, the energy conversion of mechanical sources is a significant aspect for power generators due to its easy available and no hazardous byproduct creation. Regarding harvesting mechanical energy for electrical power generation, piezoelectric materials are the prospective material for energy conversion because they have decent electrical-mechanical coupling effect. Besides, the piezoelectric microgenerator is a good option for small-sized apparatus applications (e.g. sensor nodes), particularly for dynamic systems involving mechanical vibration. Moreover, comparing to the solar or electromagnetic generators, the relative simplicity in fabrication of the piezoelectric microgenerator is remarkably appealing for use in MEMS [2].

In existing reported studies on the piezoelectric generators, White *et al* apply screen printable PZT 5H film on a cantilever structure with a proof mass in the front end to form a generator. They obtain a maximum 2μw power output at resonant frequency 80Hz [3]. Sharaf *et al* presented a micro-bubble powered piezoelectric generator used for implantable medical devices. They claim 0.25pW power output in a 4mm x 4mm area with 50Hz bubble generation if the efficiency of conversion circuit is 100% [4]. These generators usually need to be operated at a certain frequency to achieve its maximum power output. However, considering a practical mechanical vibration system, due to multi-modes of continuum, several resonances occur in a relative wide bandwidth and low frequency range. Hence, our focus in this paper is to design and fabricate a decent micromachined piezoelectric generator to harvest vibration energy in a wide bandwidth.

2 - DESIGN PRINCIPLES

Figure 1 shows the conceptual diagram of our designed microgenerator. Two major characteristics involved in the generator are described in the following:

2.1 - Low Young's Modulus supporting layer

A packaging tape serves as a supporting layer in the piezoelectric active region to form the structure of silicon nitride / bottom electrode / piezoelectric material / insulting layer / top electrode / package tape. With residue stress free and low Young's Modulus of the supporting layer, the cantilever structure could reach a better displacement, compared to a regular SOI wafer made structures [5]. Besides this, low cost and easy fabrication are further advantages of the developed process.

2.2 - Systematically design based on optimal FOM

In order to collect energy in a wide bandwidth, a systematic design approach is developed (Table 1). We study three different cases with two proof masses on each cantilever structure, which can be implemented by silicon bulk-machining and all the cases have the same total lengths. *Case 1:* Change the size (weight) ratios of two proof masses but keep the two distances between two proof-masses equal, and the sum of the two distances are constant. The special case is that when the second mass vanishes, the length of movable cantilever is one half of the total length. *Case 2:* Vary the ratios (L_2/L_1) of the distance between the second mass and the anchor to the distance between two proof-masses. Meanwhile, we maintain equal sizes (weights) of the two proof-masses in each cantilever structure, and keep the sum of sizes of two proof masses fixed. *Case 3:* Arrange the two proof masses at both ends of the cantilever, and set the movable length as one half of the total cantilever length, then adjust the ratios of two proof masses. FEA is used to find the dynamic responses of those cantilever structures according to the three cases we mentioned above.

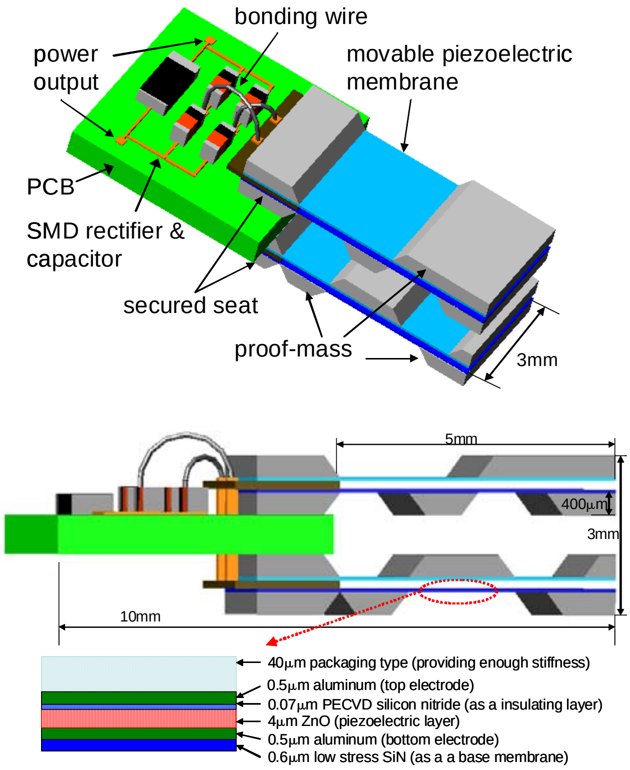
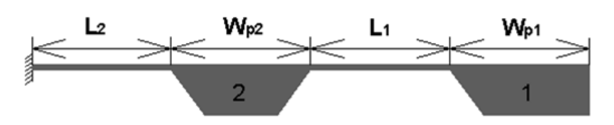


Figure 1 –Conceptual diagram of the piezoelectric wide-bandwidth microgenerator with optimal FOM structure design.

Figure 2 shows the results of bandwidth vs. different parameter ratios. The bandwidth is defined as the frequency range from DC to the fundamental resonant frequency. The results indicate case 3 has much larger bandwidth than the other two cases. However, the wide bandwidth is not only our design consideration. The amount of electrical charges produced by the devices, which is related to the displacement of the cantilever, is also significant to the performance of the power generation. Thus, in order to systematically compare the performance in the three discussed cases, we define the figure of merit (FOM) by the equation of $(\text{Bandwidth})^2 \times$ (the maximum displacement of cantilever structures under a given acceleration at static condition). Based on three curves shown in figure 3, we find that the FOM of case 3 is the smallest in three cases due to its relative little displacement. The case with largest FOM is the structure which has a bigger proof mass in the center region, and a small proof mass in the front end of the cantilever. Thus, for a given total length of cantilever with two proof-masses structures, figure 3 provides the relationship between the FOM and designed variables. Base on figure 2 and 3, we can find out the tradeoff between bandwidths and FOMs to select the appropriate design. For example, if we select the four kinds of designed structures (circled in Fig. 3), which are the points of local maximum FOMs, to be connected-in-parallel as the generator. Therefore, the generator can have relative wide bandwidth to harvest vibration energy as well as good electrical power generation. Figure 4 shows the expected power generation at 5g acceleration circumstance based on the composition of piezoelectric film: 0.8μm SiN/0.5μm Pt (Ti as a seed layer)/4μm sputtered PZT (d_{31} = -85 [6]) /0.5 μm Al/ 40μm packaging tape (as a structure supporting layer).

Table 1 –Designed parameters for FOM analysis.



Case No.	Controlled parameter (r)	Fixed conditions
Case 1	W_{p2}/W_{p1}	L_1+L_2 = const. ; $L_1 = L_2$
Case 2	L_2/L_1	$W_{p1}+W_{p2}$ = const. ; $W_{p1} = W_{p2}$
Case 3	W_{p2}/W_{p1}	$L_2 = 0$; L_1 = 1/2 total cantilever length

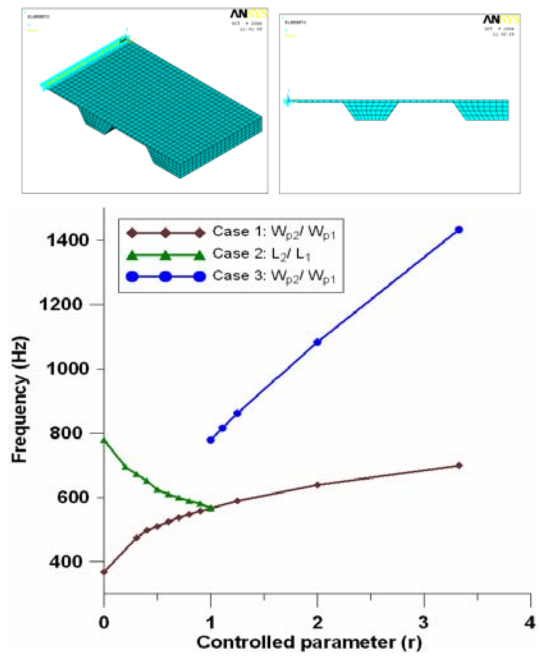


Figure 2 Bandwidth vs. the parameter ratio (listed in table 1) for different structures. The results are derived from FEA simulation (FEA model as shown on top of the figure).

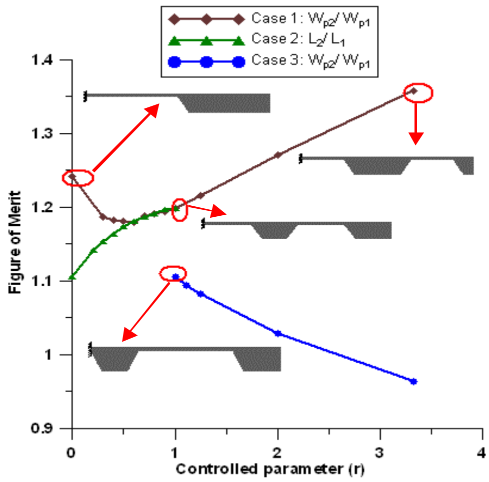


Figure 3 Figure of Merit (FOM) results (four cantilever structures with FOMs as circled points are selected for the design generator).

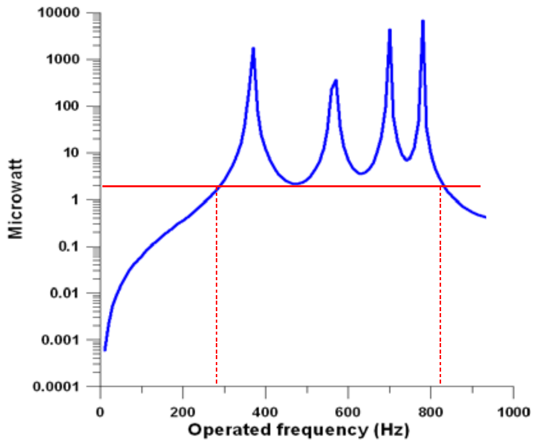


Figure 4 Estimated power generation with the power range of μW to mW in a wide bandwidth.

3 - FABRICATION PROCESSES & RESULTS

To fabricate the devices, we start with silicon bulk-machining on the 3" wafer with 0.8 μm thick low stress silicon nitride (SiN) deposited (Fig. 5). After SiN membranes are formed, we evaporate 0.5 μm thick aluminum as bottom electrodes. Then 4μm thick ZnO is sputtered and patterned. Followed by 0.07μm thick PECVD SiN deposited as an insulting layer. Then, 0.5μm thick top aluminum layer is deposited and patterned. Finally, a packaging tape is applied on top of the membrane to provide necessary stiffness of the device. In this case, we use ZnO instead of PZT as the piezoelectric layer due to its easier deposition process. As for the devices fabricated by PZT film, we will discuss in later articles. The relative lower piezoelectric constant (d_{31}) of ZnO compared to PZT is a drawback. However, the developed principle of fabrication process and design scheme is suitable for different piezoelectric materials. Thus, once the d_{31} of device is characterized, we could know the maximum power generation, which will be mentioned in the next section.

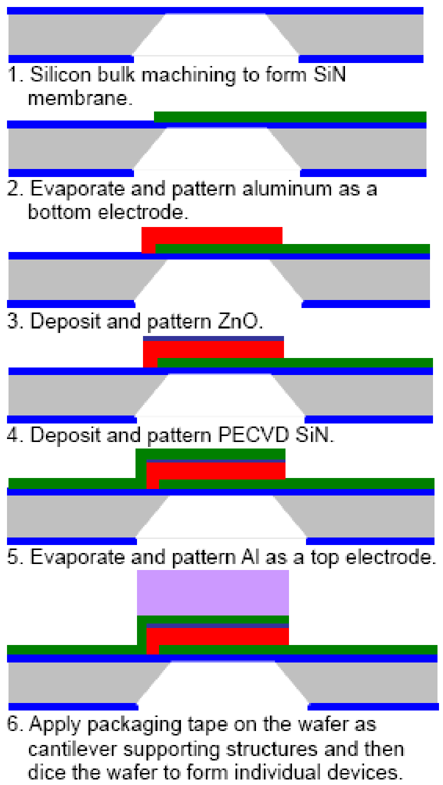


Figure 5 Fabrication process flow diagram of designed piezoelectric micro generators.

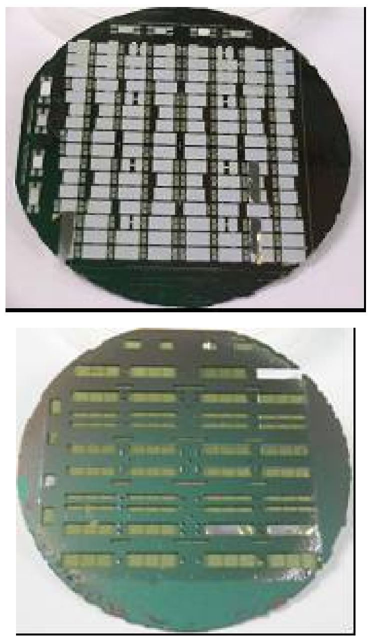


Figure 6 Front side (*top*) and backside (*bottom*) photos of the generator devices fabricated on a whole 3" silicon wafer by bulk-micromachining.

The fabricated devices on a whole 3" silicon wafer are shown in Figure 6. The layout of proof mass can be arranged by following our developed scheme which discussed in the previous section. To make individual microgenerator devices out of the whole wafer, a dicing saw is used. Figure 7 shows the diced individual devices with each size of 5mm×3mm×0.45mm. Figure 8 shows the feasibility of the generator to be integrated with a SMD rectifier and capacitor on a circuit board to construct a module and then be implemented on a dual in-line package (DIP).

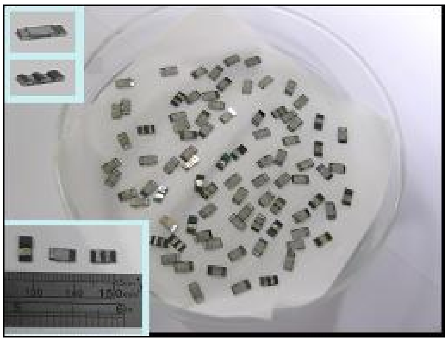


Figure 7 High yields of individual devices after wafer dicing.

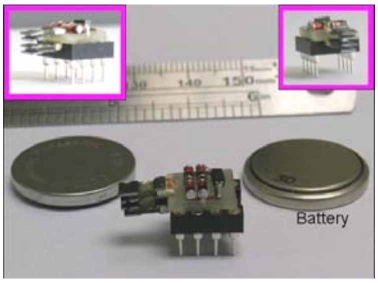


Figure 8 Integrate the microgenerator module into a DIP.

4 - DEVICE CHARACTERIZATION & DISCUSSIONS

Due to the small size of devices, the resultant low power level output, along with power consumption in probing and noise influence are issues. Consequently, the weak output signal is predictable. However, we believe these effects could be minimized by efficient power transfer circuit design, even integrated with a power conditioning CMOS circuitry [7]. Thus, our major concern is the amount of electric charges generated by the devices. To evaluate this, we use laser vibrometer to measure the center displacement of the membrane when we apply an AC voltage on the device, and then find out the piezoelectric constant (Fig. 9). Hence, the generated power can be estimated. According to the formula [8], the d_{31} value can be computed (-4.12 pC/N). The value is around one order less than that of the literature noted PZT [6].

5 - CONCLUSIONS AND FUTURE WORKS

A micromachined generator scavenging vibration energy in a wide bandwidth is developed. Different from a common single proof mass piezoelectric cantilever-beam-type generator only operated at a certain frequency, our generator is aimed at generating microwatt to milliwatt power level in the frequency range of 300-800Hz. Thus, the generator could continuously produce power for storage under a practical mechanical vibration environment. Once the generator integrates with optimized power management CMOS circuit, it will be very useful for many wireless communication applications.

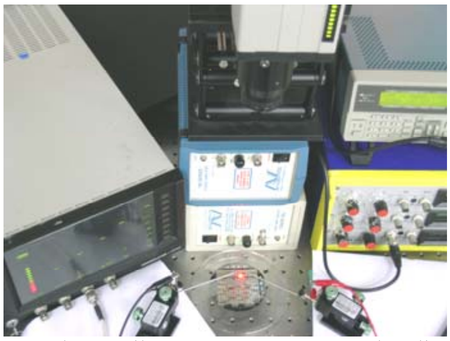


Figure 9 Use laser vibrometer to measure the displacement of devices for characterization of piezoelectric constant.

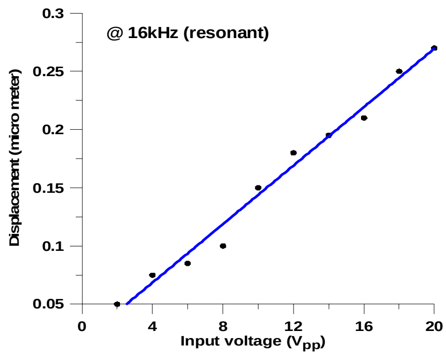


Figure 10 Relationship between displacement and voltage.

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