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To cite this article: W J Wu et al 2014 J. Phys.: Conf. Ser. 557 012027

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Comparison of the piezoelectric energy harvesters with Si-**MEMS and metal-MEMS**

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Abstract. This paper presents the development of piezoelectric energy harvesters based on silicon and stainless steel substrates, which have the ability to harvest mechanical energy from surrounding vibrations and transform vibration energy into useful electrical power. Our experimental results show that the silicon-based device had a maximum output power of $0.9 \,\mu W$ with 1.0 V_{P-P} output voltage excited at 107.9 Hz under a 0.25 g vibrating source. The metalbased device had a maximum output power of 2.7 μ W with 1.5 V_{P-P} output voltage at a vibration frequency of 108.6 Hz and 0.25 g acceleration. The areal power density was 0.02 μ W mm⁻² and 0.05 µW mm-2 for the devices based on silicon and on stainless steel, respectively. The siliconbased devices broke when the device excited exceed 0.25g acceleration, while the metal-based devices can sustained for vibration level higher than 2g acceleration. The stainless steel based device is therefore proved to be much more reliable than silicon based device.

1. Introduction

In recent years, piezoelectric material has rendered a revival of intensive research activities due to their application potential and interesting physics. Once such application, energy harvesting, has become an important issue all over the world. Comparing all possible energy sources, mechanical vibration is the potential power source that is easily accessible through micro-electro-mechanical system (MEMS) technology. Most of the studies in piezoelectric MEMS are simple a cantilever beam structure based on silicon substrates. In many MEMS energy harvesting studies, to obtain high output power, it has been shown that the performance of the d_{31} mode was greater than the d_{33} mode [1]. Therefore, we used the d_{31} mode for research presented in this paper. For applications with high acceleration levels, PZT material on silicon or silicon on insulator (SOI) substrates can cause cracks owing to the brittle mechanical properties of silicon. To increase the ultimate mechanical strength of piezoelectric MEMS, finding an alternative substrate material becomes necessary.

In this paper, we show the development and construction of homemade PZT deposition equipment for the aerosol deposition method, which can deposit PZT thin films on traditional silicon substrates (silicon-based) and stainless steel substrates (metal-based) as well. We compare the two different substrate based devices by using the same laminate structure, sandwiched between top and bottom electrodes. In order to lower the resonant frequency matching with the low frequency vibrations in ambient, we designed the cantilever beam structure to operate at an appropriate resonant frequency to maximize the displacement of PZT thin film. Finally, we present a comparison of output power and lifetime between silicon-based and metal-based devices in long-term vibrating cycles.

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2. Fabrication of PZT layer by aerosol deposition system

Lin et al. shows a schematic diagram of a homemade equipment to deposit PZT thin film based on aerosol deposition method [2]. The advantage of the aerosol deposition better over tradition methods is a more compact texture than that of screening printing is obtained and an easier pattern definition can be produced with simple shadow masks. However lift-off process is used in this study instead of shadow masks to define PZT patterns because of better resolution.

3. Substrate fabrication

3.1. Silicon substrate

Standard processes for silicon-based substrates have been have already been studied [3]. We therefore used a traditional process to make the devices on SOI substrates. We acquired a SOI substrate with a laminar structure of Si 60 μ m/SiO₂/Si 350 μ m. The SEM photograph of the cross-sectional view of the device structure is shown in Figure 3-1. Figure3-2(a)(b) shows photographs of fabricated devices.



Figure 3-1 SEM photograph of a cross-sectional view of the cantilever-beam with a PZT layer of 10 µm based on a silicon substrate.



(a) (b) Figure 3-2 Photographs of the devices: (a) after beam released structure, (b) a single device

3.2. Stainless steel substrate

In order to compare the difference between silicon-based and metal-based piezoelectric MEMS, we deposited the same PZT layer thickness of 10 μ m on 60 μ m stainless steel substrates. Lin et al. shows the fabrication process of metal-based devices [2]. The SEM photo of the sidewall and cross-sectional

view of PZT/stainless steel samples after the lift-off process are shown in Figure 3-3 (a)(b). Fabricated devices are shown in Figure 3-4 (a)(b).



Figure 3-3 SEM photograph of the device after deposition: (a) the sidewall, (b) cross-sectional view.



Figure 3-4 Photographs of the devices: (a) a single device and (b) side view of the beam

4. Results and Discussion

Lin et al. shows the experimental setup [2]. The output power and output voltage of the device was measured with a optimal resistive load. The output average power can be expressed by the equation [6]

$$P = \left(\frac{V_{p-p}}{2}/\sqrt{2}\right)^2 / R ,$$

where V_{p-p} is the load output voltage of peak-peak values and R the load resistance.



Figure 4-1 Experimental results of output voltage vs. frequency at 0.2 g acceleration

In order to compare the difference between the silicon-based and the metal-based devices, both devices were poled under 5 V μ m⁻¹ for 1 hour after then annealing processes. The results of output voltage dependent frequency are shown in Fig 4-1. The resonant frequency and output voltage was observed within the temperature range investigated.

d ₃₁ mode with 10 µm PZT	Stainless steel base	Silicon base
Excitation Frequency	108.6 Hz	107.9 Hz
Capacitance	9.8 nF	8.6 nF
Load impedance	150 kΩ	150 kΩ
Power Output	2.7 μW	0.9 µW
Voltage Output (with load)	1.5 V _{P-P}	1.0 V _{P-P}
Quality factor Q	72.8	136

Table 4-1 Output performance of these two device at 0.25 g acceleration.



Figure 4-2 Lifetime of the two devices: (a) excited at 0.1 g and (b) excited at 0.25 g.

The excitation of the silicon-based and metal-based devices was similar because the Young's modulus of silicon and stainless steel is almost the same (about 200 Gpa). Table 4-1 also shows that the capacitance of each device. Although the same laminated structure was used for each device, the total area of the laminated structure on the metal-based devices was larger than silicon-based devices. Therefore the capacitance of the metal-based devices was larger than that of the silicon-based devices. The results show the output performance of the device on stainless steel was better than the silicon-based device.

The result of the lifetime test at 0.1 g and 0.25 g acceleration level is plotted in Figure 4-2. At 0.1g low acceleration vibration excitations, both devices works continuous for more than 7 days. For slightly higher vibration level of 0.25g acceleration, the silicon-based device was observed to crack after 10 minutes.



Figure 4-3 The ultimate exciting acceleration of the two devices

However, the metal-based device was still working at the 0.25 g acceleration level for hours. The cracked silicon-based device is shown in the photos of Figure 4-3. The real power density was 0.02 μ Wmm⁻² and 0.05 μ Wmm⁻² for the silicon-based and the metal-based device, respectively. Finally, we measured an ultimate exciting acceleration for both devices. The result was plotted in Figure4-3 and the crack behaviour was observed. The results show that the metal-based device can sustained vibration level up to 2g acceleration thanks to the flexibility of stainless steel substrates while the silicon based device all broken around 0.25g. This results shows the metal based devices have much better mechanical strength and reliability compared with silicon-based devices.

5. Conclusions

In summary, the PZT thin film was successfully deposited on silicon and stainless steel substrates by a homemade aerosol deposition machine. The devices based on traditional silicon substrates had a maximum output power of 0.9 μ W with 1.0 V_{P-P} output voltage excited at 107.9 Hz under a 0.25 g vibrating source. The device based on a stainless steel substrate had a maximum output power of 2.7 μ W with 1.5 V_{P-P} output voltage at a vibration frequency of 108.6 Hz at 0.25 g acceleration. Our results also shows that the silicon-based device had a longer lifetime than silicon-based device. The metal based devices can sustained vibration levels up to 2g acceleration while the silicon based devices all broken around 0.25g acceleration. All the results demonstrate that metal-based devices have better performance and also much better reliability compare with silicon-based devices.

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