Mechanical Design and Material Characterization of the Piezoelectric Energy Harvestor

M Ichiki[1], E Komine[2], K Sueshige[2], K Iimura[2], T Kobayashi[1], T Kitahara[3] and S Fujimoto[4]

[1] National Institute of Advanced Industrial Science and Technology(AIST), Tsukuba, 305-8564,Japan
[2] the University of Tokyo, Tokyo, 113-8656,Japan
[3] Shonan Institute of Technology, Fujisawa,251-8511, Japan
[4] Tokyo City University, Tokyo, 158-8557 Japan

E-mail: ichiki-m@aist.go.jp

Abstract. This paper is on the proposal of the methodology for the design and fabrication of the piezoelectric energy harvesting devices in viewpoint of the justification both structural and material properties. There has been developing various kinds of energy harvesting techniques using piezoelectric films. Most of them are for the justification of the design or the circuit. The output of the piezoelectric harvester is the product of the material and structural parts. It is, therefore, necessary to justify both of them simultaneously. In this paper cantilever structure was fabricated for the improvement of the power generation in the low frequency region. The resonant frequency and output voltage and charge from the following theory formula were calculated in this study.

1.Introduction

There has been increasing technological demand to develop the energy harvestor using ambient vibration for the application for ubiquitous micro devices and systems[1][2]. Piezoelectric energy harvestor is one of the techniques of the applicable for transducer from the mechanical to electrical energy. The advantage of piezoelectric type is in its simple structure of smart materials and also the high energy conversion efficiency. MEMS piezoelectric harvestor has been developing with use of microfabrication technology and thin films[3]-[8]. Micro vibrational harvestor devices, like cantilever type have its resonant frequency over 1kHz in its earlier stages[3]. On the other hand, ambient environmental vibration has normally its resonant frequency in lower frequency region of 1-100Hz. The vibrational devices have its maximum output at its resonant frequency. It is, therefore, necessary to develop such device structure as has low resonant frequency that is useful for ambient environmental vibration. In addition to frequency requirements, it is also necessary to establish the methodology to justify the device structure and the choice of piezoelectric materials for the expected applications.

The output of the harvestor devices are shown to be as equation (1). The right term is divided into the multiple of the 2 parts ; one is on the material characterization and the other one is on the size of the device. It is, therefore, necessary to justify both the material and also the size of the device for the realization of the maximum performances. In this article two approaches will be shown for the improvement of the piezoelectric energy harvestors. One is the methodology of the justification of the size of cantilever devices. Computational solution will be obtained for the high output with low frequency. The other one is comparison of the resonant frequency obtained by simulation and experiment. The thickness of the device Si layer was shown to be effective to the output of the devices.

2. Method and Process

Output charge will be equation (1) using a simplified model of the device shown as Fig.1. Capacitance becomes equation (2) assuming that piezoelectric is a capacitor, therefore the output voltage can be calculated equation (3). It is considered by formula (3) that characteristics of the device will be determined by the structural shape and material parameters. Equation (4) is the resonance frequency equation and is derived from a spring mass model of Si only. Q is the generated charge in this system. d, E, F, K are piezoelectric constant, Young' modulus, induced force and coupling constant. Those are based on the material properties of the piezoelectric films

The dimension of the cantilever structure was examined using the finite element analysis for the justification. In this study, these theoretical calculations and finite element analysis carried out for the confirmation of the effectiveness of structural design and material composition. This structure is typical in case of piezoelectric MEMS energy harvestor using SOI wafer[ ] . The fabrication process is typical and was shown in previous work[ ]. The measurement of resonant frequency was carried out using laser Doppler vibrometer.

The justification of the size of device was made for the specification the length of the beam that is kept as total length. The proportion of the beam with mass and without mass was justified for the realization of the high output at low frequency region. The comparison of the simulated and experimental results of resonant frequency will be shown with different thickness of device Si layer of SOI wafer. Simulation was made with use of FEM method.

$$Q = \frac{d_{31} E_{PZT} F}{K_f} w(y_n - h_1)(\frac{L^2}{2} + \alpha L) \tag{1}$$

$$C = \varepsilon_{PZT} \frac{wL}{h_{PZT}} \tag{2}$$

$$V = \frac{Q}{C} = \frac{\frac{d_{31} E_{PZT} F}{K_f} w(y_n - h_1)\left(\frac{L^2}{2} + \alpha L\right)}{\varepsilon_{PZT} \frac{wL}{h_{PZT}}} \tag{3}$$

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}} = \frac{1}{2\pi}\sqrt{\frac{E_{Si} h_{Si}^3}{8\rho_{Si}\alpha h_m (L+\alpha)^3}} \tag{4}$$

3.Experimental Results

It was found that L = 2.5mm, α=1.25mm, h_{si} = 9μm, h_{PZT} = 2μm cantilever was optimal for the low resonant frequency and high output voltage by changing the dimensions in the equation (3) and (4) . Fig.2 show the output charge and voltage using the dimension value and the value of material properties. Charge is dependent on the Young's modulus and piezoelectric constant. Nb doped PZT has the largest piezoelectric constant. On the other hand, voltage is dependent on the dielectric constant, ZnO has the lowest dielectric constant among the materials in Table. According to these results, it is expected that Nb doped PZT which have high piezoelectric constant shows higher output. And similar tendency is also expected to KNN.

Output voltage was calculated by using finite element analysis software: MemsONE. Simulation procedure for the output voltage is examined and established as follows. 1) Determine the displacement by using the harmonic response analysis. 2) Voltage was determined from the displacement by piezoelectric analysis. The thickness of the device Si Layer is shown to be effective to the resonant frequency. The comparison of the resonant frequency of the simulated ans experimental is in good coincidence. Fig.3 shows the results of calculation of the resonance frequency. Among them type 2 has the highest output and low frequency. But this type is difficult because of the heavy mass. In the following sections type1, 3 and 4 will be compassioned in FEM and also the measurement of the devices. Fig.4 shows the results of the output voltage at 100Hz. Based on the results of theoretical calculation and finite element analysis, high output of the actual device is expected by changing the material composition.

Fig.5 shows the compassion of the resonant frequency and the thickness of device-Si layer of type 1 device. The resonant frequency has linear relationships with the thickness of device Si.

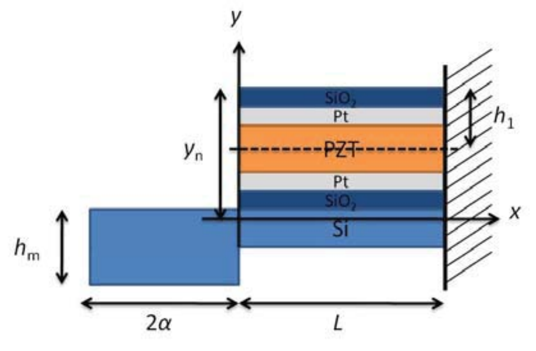

Figure 1. Simplified model of the device.

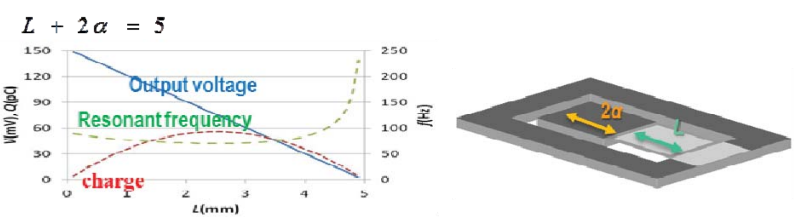

Figure 2. The structure of the devices and the computational results of the resonant frequency and output

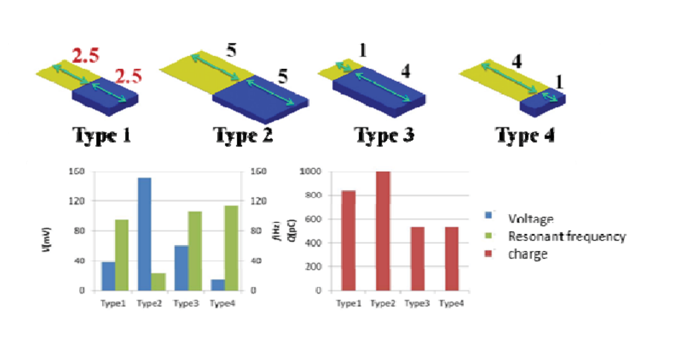

Figure 3. Simulated results of voltage, resonant frequency and charge of the 4 types of cantilever devices

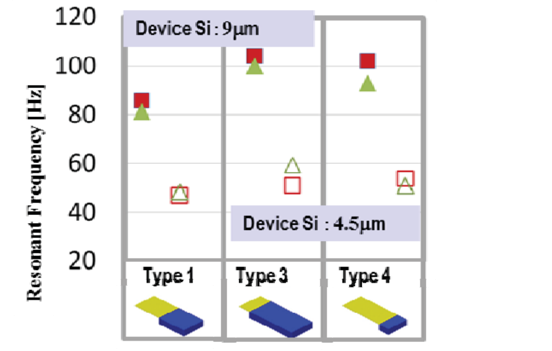

Figure 4. Comparison of the simulated and experimental resonant frequency of different size with their schematic figure

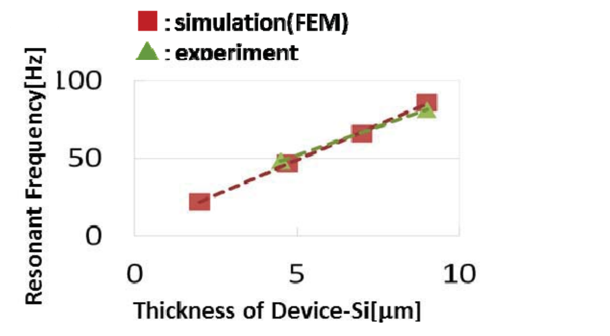

Figure 5. The relationships between the resonant frequency and the thickness of Device Si layer

4.Discussions and Summary

In this article design and simulation of the piezoelectric cantilever structure was carried out. Justification of the size was made and to be shown the most suitable structure of the energy harvestor. The resonant frequency of the same devices was simulated to obtain the resonant frequency. The resonant frequency was shown to be strongly depend on the thickness of the device Si layer. The relationship was linear. The following results was mainly shown. 1) One of the optimization methods was shown. MEMS cantilever structure was examined and shown to be its optimised size. This is estimated using maximum output voltage and low resonant frequency. 2)The justification of the simulation and experimental value of the resonant frequency was carried out. The thickness of the device Si Layer is shown to be effective to the resonant frequency. In the optimization of the device structure, the 2.5mm-mass and 2.5mm-cantilever structure was most suitable for low resonant frequency and high output. As a result, the method of the justification of the size of device was established in the above procedure. The coincidence of the simulated and experimental is in good. The thickness of the device Si layer is affective to the output of the harvestor.

References

[1] Feng Y, Hagiwara K, Iguchi Y and Suzuki Y, 2012, Appl.Phys.Lett, 100, p.262901.
[2] Liu H, Zhang S, Kathairesan, Kobayashi T and Lee C, 2012, Appl.Phys.Lett, 100, p.223905.
[3] Kobayashi T, Okada H, Masuda T and Itoh T 2009 Tech. Digest of MEMS 2009 Conference, Sorento, p.801
[4] Renaud M, Karakaya K, Sterena T, Fiorini P, Van Hoof C, and Puers R 2008 Sensors and Actuators A **145-146**, p.380.
[5] Elfrink R, Kamel T M, Goedbloed M, Motova S, Hohlfeld D, van Andel Y and van Schaijk, R, 2009, J. Micromech. And Microengineering,**19**, p.094005-14
[6] Shen D, Park J H, Noh J H, Coe s Y, Kim S H, Wikle III H C and Kim d J, 2009, Sensors and Actuators A, **154**, p.103.
[7] Miller L M, Halvorsen E, Dong T and Wright P K, 2011, J. Micromech. And Microengineering, **21**, p.045029-1
[8] Cook-Chennault K A, Thambi N, and Sastry A M, 2008, Smart Materials and Structures, **17**, p.43001-1.

Acknowledgments

This work was partially supported by the Presto JST. The authors express their thanks to K.Tanaka and M.Obata(AIST) for their preparation of the sample treatment. We will show our grateful to Dr.R.Maeda and Dr.T.Itoh(AIST) for their encouragement during this study. This work was partially supported by Grant-in-Aid for Scientific Research, 25420196(KAKENHI) program.