ASSEMBLING OF THICK PZT SHEET ON SILICON FOR ENERGY HARVESTING APPLICATIONS

Pattanaphong Janphuang[1*], Don Isarakorn[1, 2], Andres Vásquez Quintero[1], Robert Lockhart[1], Jinyu J. Ruan[1], Danick Briand[1] and Nico F. de Rooij[1]
[1]Ecole Polytechnique Fédérale de Lausanne (EPFL), Institute of Microengineering (IMT), Sensors, Actuators and Microsystems Laboratory (SAMLAB), Neuchâtel, Switzerland
[2]Department of Instrumentation and Control Engineering, Faculty of Engineering King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand
*Presenting Author: pattanaphong.janphuang@epfl.ch

Abstract: This paper reports on the fabrication and characterization of vibration energy harvesting devices based on the assembling of thick PZT on a silicon substrate designed for a frequency range of 100-200 Hz. Bonding techniques were investigated to bond thick PZT sheet on silicon using a test structure to compare their associated electromechanical (piezoelectric) coupling coefficient (k^2). Compared to the gluing and soldering, dry foil photoresist with its good electromechanical coupling coefficient is of interest for a transfer of PZT sheet by lamination on different types of substrates. These bonding layers were implemented in resonant piezoelectric harvesters with a normalized output power of 4.08 mW/cm^3/g^2, which is of interest for practical applications in the field of energy harvesting from vibration.

Keywords: Energy harvesting, Thick PZT sheet, Bonding, Dry foil photoresist

INTRODUCTION

Energy harvesting is nowadays attracting an amount of interest as a means for powering low power consumption devices and various types of sensors such as small wireless sensor networks, structural health monitoring, environmental condition monitoring and biomedical implants. During the past few years, the development of energy harvesting devices to convert mechanical energy from vibrations into useful electrical energy has rapidly advanced because motions and vibrations are the most ambient energy source available, like in industrial machines, transportations, household goods, and human body. A large number of vibration based energy harvesting devices have been proposed using three mechanisms, including electromagnetic, electrostatic and piezoelectric. Among them, piezoelectric materials have received much attention due to their self contained power without necessity for external power source, high energy density, ease of integration into a system, and potential miniaturization [1].

Bulk piezoelectric ceramic materials present high electromechanical coupling which is highly desirable in piezoelectric energy harvester since the energy transformed from mechanical to an electrical form is proportional to the k^2 [1-3]. Several piezoelectric cantilever based energy harvester with bulk PZT have been proposed and investigated in recent years [4-5,7]. They require a bonding layer to transfer the thick PZT sheet on elastic layer substrate, mostly on silicon. In this paper, we present the characteristics and performance of the thick PZT sheet bonded on silicon using different techniques for vibration energy harvesting. We also introduce the use of a dry foil photoresist as a bonding interface between piezoelectric thick sheets and different types of substrate. Dry foil photoresist present real advantages with a defined thickness, good adhesion to different materials (metal, glass, silicon, and plastic substrates) patternable using photolithography and the use of as transfer process.

INVESTIGATION OF BONDING METHODS

A key challenge that has to be considered when it comes to fabrication of bulk piezoelectric MEMS harvester is the integration of piezoelectric layer onto silicon substrate. Since the power output from piezoelectric harvester is directly proportional to the electromechanical coupling coefficient. In order to achieve high energy transformed from mechanical to electrical, the bonding techniques and materials used as an intermediate layer are taken into account.

In this work, the bonding of thick PZT sheet on silicon by using UV activated glue (DELO 4552), a dry foil photoresist (PerMX3014), and low temperature soldering (BiSn) were investigated on the test structure as illustrated in Fig. 1.

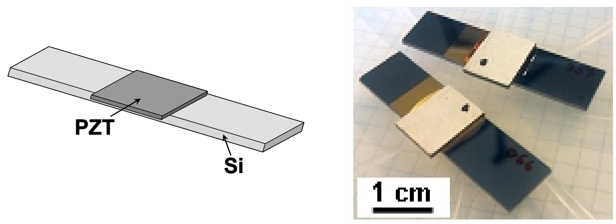


Fig 1. Test structure configuration of the thick PZT sheet (1cm×1cm×0.1cm) on silicon substrate (1cm×4cm×0.1cm).

The test structures were then characterized by using impedance analyzer (Agilent 4294A) to excite the structure electrically. The coupling coefficient of each device was determined from the difference between the resonant and antiresonant peaks [6] as listed in table 1 with good results for the dry foil photoresist.

Table 1. Resonant (f_r), antiresonant (f_a) frequency and calculating of k^2

$$k^2 = 1 - \left(\frac{f_r}{f_a}\right)^2$$

Bonding materials	f_r (kHz)	f_a (kHz)	k^2 (%)
Spin coated epoxy (10 µm)	4.78	4.84	2.38
Dry foil resist (14µm)	4.82	4.90	3.09
Soldering (BiSn) (30 µm)	4.98	5.04	2.41

DESIGN AND FABRICATION

The frequency range of the ambient vibration of interest in environment is in the order of 60-200 Hz [1,3,6-9]. The energy harvesting device needs to be designed to match such low frequency in order to obtain the optimum output power. The design of the thick PZT sheet harvester in this work is based on unimorph cantilever with proof masses at the free end (Fig. 2).

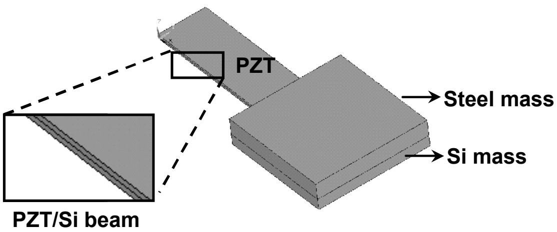


Figure 2. Schematic of a unimorp cantilever with proof mass energy harvester

The supporting layer and the proof mass are made from silicon and another heavy proof mass (stainless steel) is added on the top of silicon mass to degrease the resonant frequency of the structure lower than 200 Hz. The 130 µm-thick PZT-5A is used as piezoelectric layer, which is located on the top of supporting layer and is operated in transverse (d_{31}) mode. The design parameters of the thick PZT sheet harvester are given in table 2.

Table 2. Thick PZT sheet harvester design parameters

Piezoelectric volume (mm^3)	Beam volume (mm^3)	Mass (Si) volume (mm^3)	Mass (Steel) volume (mm^3)
3×8.5×0.130	3×8.5×0.130	7×7×0.525	7×7×1

The thickness ratio of the bender (t_{PZT}/t_{Si}) is one of the key paremeters in the design. As demonstrate in [7], to maximize output power generated from the harvester, the thickness ratio of the bender must be close to 1. The resonant frequency of the thick PZT harvester was first simulated by finite element method (FEM) in ANSYS. The result reveals that the resonant frequency of the thick PZT harvester is of about 187 Hz (Fig. 3).

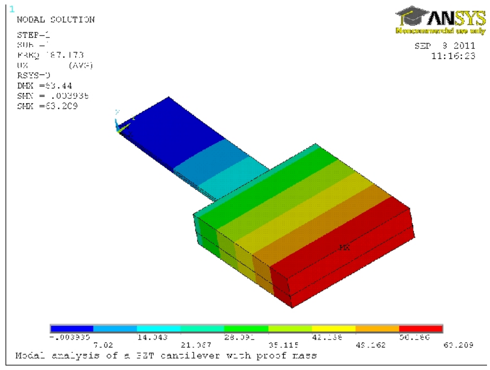


Figure 3. Result of FEM simulation for the first vibration mode of the beam at its resonant frequency.

The fabrication process of the thick PZT sheet harvester is illustrated in Fig. 4. The process starts from 100 mm in diameter and 525 µm-thick silicon substrate. The shape of cantilevers is first patterned from the top side by DRIE (Fig. 4(a)). A 200 nm-thick LPCVD silicon nitride film is then deposited on both side for electrical isolation and used as during the KOH etching of silicon. Backside openings in the silicon nitride are defined using UV lithography followed by RIE etching (Fig. 4(b)). The exposed silicon areas are wet etched in a KOH solution to accomplish the silicon cantilever with proof mass (Fig. 4 (c)). The bonding of 130 µm-thick PZT covered with nickel electrodes is performed using the same bonding techniques that have been used on the test structures, which are spin coated UV curable epoxy, lamination of dry foil photoresist as a bonding layer, and low temperature soldering using BiSn (Fig. 4(d)). Finally, the stainless steel proof mass is bonded on top of silicon mass by using epoxy (Fig. 4(e)).

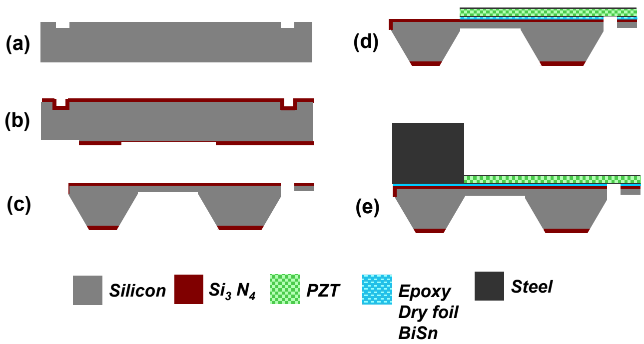
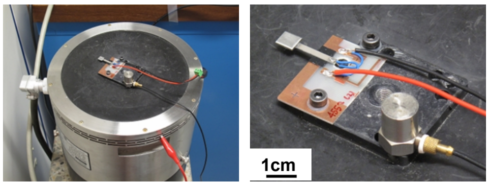


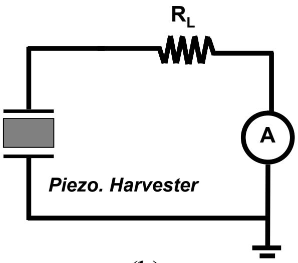
Figure 4. Fabrication of thick PZT sheet harvester: (a) DRIE (b) deposition of silicon nitride and RIE on backside (c) KOH etching on the backside (d) bonding of PZT with metallic electrodes (e) bonding of steel proof mass.

EXPERIMENTS

The energy harvesting performance of the thick PZT sheet harvesters were investigated with an electrodynamic shaker (Brüel & Kjær type 4811), by applying an oscillation at varying frequency and acceleration as a mechanical input. The harvesters were mounted on the shaker and connected directly to various resistive loads R_L. Since piezoelectric is acted as a capacitor, an ac current generating through a resistive load under different acceleration levels was recorded by current meter (Fig. 5). The average power dissipated in resistive load (R_L) is calculated by $P_{ave}=I^2_{rms}R_L$.



(a)



(b)

Figure 5. (a) Optical images of the fabricated harvester mounted on the shaker (b) electrical measurement scheme.

RESULTS AND DISCUSSION

The resonant frequency of the thick PZT harvester made by gluing and lamination of dry foil photoresist are found at 164.1±5 Hz and 167.8±4 Hz respectively. The measured value is lower than the result from simulation because of the size of steel mass. The actual size of the steel mass is found to be 7.6×7.6×1 mm^3, which is higher than simulation, resulting in lower resonant frequency. The resonant frequency of the thick PZT harvesters made by soldering are found at 226.8±8 Hz. Because the thickness of BiSn interface layer is up to 60 µm, the resonant frequency of these devices is higher than the simulation.

The electromechanical coupling coefficient (k^2) of each device was experimentally determined from the frequencies shift between open circuit and short circuit conditions allow us to estimate the k^2 of the harvester [9].

$$k_{eff}^2 = \frac{\omega_{o.c.}^2 - \omega_{s.c.}^2}{\omega_{s.c.}^2} \qquad (1)$$

where $\omega_{o.c.}$ and $\omega_{s.c.}$ are the open circuit and short circuit resonant frequencies.

Figure 6. gives an example of the measured output power as function of the frequency from the device made by glue at open circuit condition (R_L=1MΩ) and short circuit condition (R_L=100Ω). The calculations of k^2 for all devices are given in Fig 7.

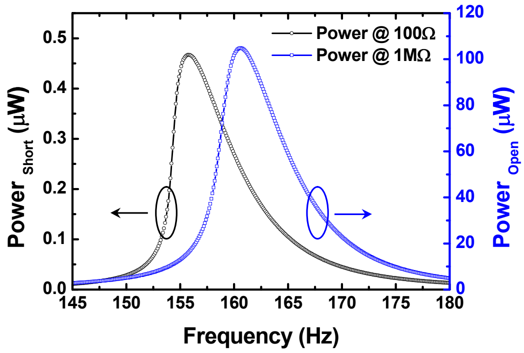


Figure 6. The output power as function of frequency and load resistance at acceleration of 1g.

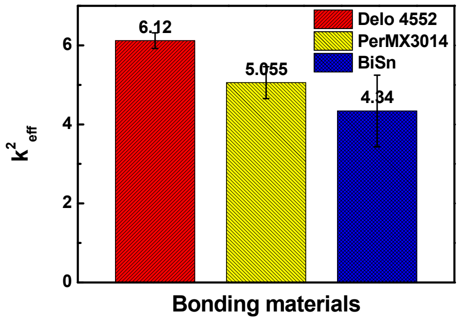


Figure 7. The calculated electromechanical coupling coefficient (k^2) of the thick PZT harvester with different bonding layers.

The devices made by glue exhibit a good electromechanical coupling coefficient compared to dry foil photoresist and soldering. One possible reason is that the thickness of the glue layer is smaller than the others, which can provide good mechanical properties [10]. Another possibility is that the bonding of thick PZT sheet on silicon was done on a chip level, therefore the dry foil were not fixed well on small pieces of PZT on the bonding machine and also to the screen printed of BiSn solder in case of soldering.

Afterwards, the output power of each device was measured under different acceleration from 0.1g to 1g at their resonant frequency. The optimal resistive load of the devices made by glue and dry foil photoresist are found to be 218kΩ and 118kΩ for the devices made by soldering at acceleration of 1g. This is because of the optimal resistive load related to the resonant frequency and capacitance of the piezoelectric layer as (R_{opt}= $1/\omega_r C_p$) [8-9].

The output data presented in Fig. 8 shows that the output power from the thick PZT sheet harvesters are proportional to k^2. The devices made by glue exhibited higher output power because of higher k^2. Moreover, the different devices made using dry foil shown a better reproductibility of the generated power compare to the others which shows a potential for a wafer level fabrication. The lowest output power obtained from the devices made by soldering due to high thickness of intermediate layer (BiSn). Since the thickness of solder layer is about of 60 µm, it increases the stiffness of the structure and reduces the strain acting on the piezoelectric material [11]. The thicker bonding layer could also reduce the electromechanical coupling of the structure resulting in low generated out put power.

Figure 9 shows an example of the average power of the device made by glue at optimal load resistance and different acceleration. An average power of power of 3.68 μW was obtained under 0.1g (166.1 Hz) and reached to 177.11 μW at 1.0g (160.6 Hz). The resonant frequency slightly decreased with the high acceleration is associated to the increasing of elastic compliance of PZT due to nonlinear effect under large stress [8]. The quality factor of this device is found to be 26 and the half power bandwidth of 9.5 Hz at the input acceleration of 1g.

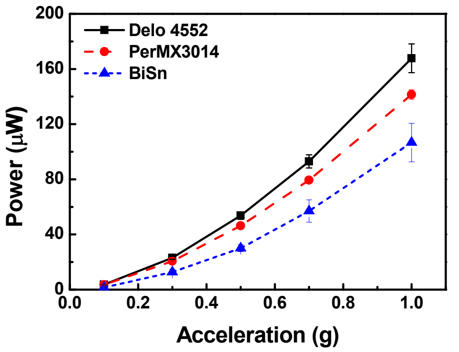


Figure 8. Power output as a function of acceleration

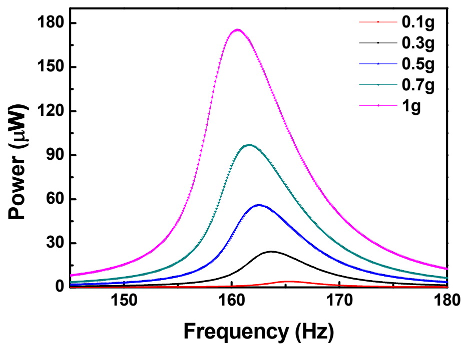


Figure 9. Output power as a function of frequency and acceleration ranging from 0.1g to 1g

CONCLUSION

Bonding techniques to transfer the thick PZT sheet to silicon substrate for energy harvesting application have been investigated in this work. PZT/Si bonding technology enables us to directly utilize a large electromechanical coupling of bulk piezoelectric materials, which is required for piezoelectric energy harvester. The design, fabrication and characterization of the thick PZT sheet harvesters with different bonding layers using UV activated glue, dry foil photoresist, and low temperature soldering were presented. Using the glue as intermediate layer achieved highest coupling coefficient but the dry photoresist also achieved coupling coefficient of interest and represents a great potential for wafer level fabrication of the thick PZT sheet harvester. Our next step is to fabricate harvesters at the wafer level using thinner PZT sheets for optimized performances.

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