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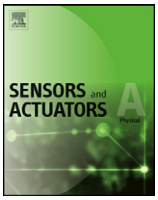

Micromachined PZT cantilever based on SOI structure for low frequency vibration energy harvesting

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ABSTRACT

A PZT piezoelectric cantilever with a micromachined Si proof mass is designed and fabricated for a low frequency vibration energy harvesting application. The SiO_2 layer in the SOI wafer promotes accurate control of the silicon thickness that is used as a supporting layer in the cantilever beam structure. The entire effective volume of the fabricated device is about 0.7690 mm^3. When excited at 0.75g ($g = 9.81$ m/s^2) acceleration amplitude at its resonant frequency of 183.8 Hz, the AC output measured across a resistive load of 16 kΩ connecting to the device in parallel has an amplitude of 101 mV. The average power and power density determined by the same measurement conditions are, respectively, 0.32 μW and 416 μW/cm^3.

1. Introduction

The boost in the technology of miniaturization of mobile electronic systems such as wireless sensors has been driving the development of small-volume and long-lasting power sources because traditional power sources such as batteries impeded this progress by having a large volume and a limited lifetime. Energy harvesting is an attractive concept because so many energy sources such as light, heat, and mechanical vibration that exist in our ambient living could be converted into usable electricity [1]. Among them, mechanical vibration energy has been intensively studied because it exists almost everywhere in our living environment and it can be readily and efficiently converted to electricity by three different electromechanical transducers: electrostatic, electromagnetic, and piezoelectric. In comparison with the former two transducers, piezoelectric transducers have advantages such as simpler configuration, higher conversion efficiency, and more precise control of the mechanical response.

With the large amount of successful demonstrations in bulk-scale piezoelectric energy harvesting prototypes [1–3], research has focused on developing more practical MEMS devices [4–10]. However, there is no report on micromachined piezoelectric cantilever having a resonant frequency range of between 60 Hz and 200 Hz, which is the frequency range of common environmental vibration sources [1]. Two difficulties slowed down the development of MEMS piezoelectric energy harvesting devices: the fabrication of high-quality piezoelectric thin film and the tuning of the resonant frequency of the device suitable for certain vibration environments. At the very beginning, ZnO thin film was used as the piezoelectric energy harvesting material due to ease of fabrication, but the low piezoelectric constant obstructed further development. Since high quality Pb(Zr,Ti)O_3 (PZT) thin films were obtained in energy harvesting device fabrication, they have become the major interest in MEMS technology due to their high electro-mechanical coupling coefficient. However, the tuning or controlling of the resonant frequency of a piezoelectric energy harvesting device is rarely studied because of the difficulties in the resonant frequency modeling for multilayer structures and in the dimension-precise control of a device during fabrication, which decides the resonant frequency.

We studied the design and fabrication of a multilayer unimorph thin film PZT cantilever with micromachined Si proof mass based on an SOI (silicon on insulator) structure for low frequency vibration energy harvesting application. A cantilever

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structure is constructed with a Pt/PZT/Pt/Ti/SiO_2/Si/SiO_2 multilayer, and the device volume (beam and mass) is about 0.7690 mm^3. The measured average power and power density from a resistive load of 16.0 kΩ connecting to the device in parallel at the 0.75g (g = 9.81 m/s^2) acceleration amplitude and at its resonant frequency of 183.8 Hz are, respectively, 0.32 μW and 416 μW/cm^3. The difference between the calculated and measured resonant frequency was 4.25% and the discrepancy becomes smaller compared with the micromachined cantilevers on conventional silicon wafer (Pt/PZT/Pt/Ti/SiO_2/Si/SiO_2), which is mainly due to the precisely controlled thickness of the silicon supporting layer. In addition, by taking advantage of the support beam and the stress-free (low stress) active silicon layer in the SOI wafer, the whole structure becomes more flat and the cantilever exhibits a much smaller curvature as preferred.

2. Analysis

The resonant frequency of a vibration energy harvesting device is one of the most important design parameters because the maximum output power density can be obtained when the vibration frequency matches the resonant frequency of the piezoelectric resonator. It has been reported that the power output will be dramatically reduced when the driving vibration frequency deviates from the resonant frequency of a device [11]. The common environmental vibrations, such as those found in a building, exhibit moderate amplitudes (<1g) and lower frequencies, typically between 60 Hz and 200 Hz [1]. The designed vibration frequency in this effort is approximately 142 Hz. A cantilever structure with a proof mass at the free end tip was chosen because this structure allows a low resonant frequency and larger strain generations under a given input force compared to other structures, such as all clamped membrane and clamped–clamped bridge. For the electrode design, two modes, such as 31 [4,5,10] and 33 [6], can be considered. Although the electro-mechanical coupling coefficient for the 33 mode is larger, we used the 31 mode since the orientation and crystallization of PZT film can be modulated on a Pt metal electrode (31 mode design) while PZT film on oxide layer (33 mode design) typically produces random orientation and higher crystallization temperature.

The schematic of the designed multilayer PZT cantilever energy harvest device is shown in Fig. 1. The whole structure was based on a SOI wafer. Si at the free end tip was used as the proof mass to decrease the resonant frequency. Si between silicon oxide layers was used as a supporting layer to improve the mechanical strength of the beam and to prevent the beam from bending in static status due to internal stress. Such internal stress is mainly due to the residual stress generated during high temperature process and different thermal expansion coefficients. SiO_2 was used as the insulator between the bottom electrode Pt/Ti and Si and to compensate for the internal stress. Ti was used as the adhesion layer to improve the adhesion between PZT and Pt and to facilitate the growth of the PZT crystal. Pt was used as the electrode.

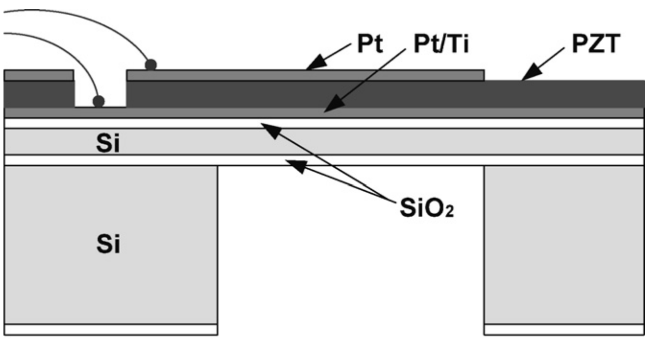

Fig. 1. The schematic of the side view of a piezoelectric energy harvesting cantilever based on a SOI wafer.

The dimension of the device was first designed to match the resonant frequency by a calculation with the pre-decided thicknesses of layers. The thickness of the proof mass and the thickness of the Si supporting layer were limited by the commercial 100 mm (4 in.) SOI wafer, approximately 500 μm and 20 μm, respectively. The thickness of PZT thin film was fixed around 1 μm. All other thinner layers, such as Pt, Ti, and SiO_2, were ignored to simplify the calculation except for thickness. We assume that the thickness of PZT layer includes the total thickness of Pt/PZT/Pt/Ti layers, and the Si layer does SiO_2/Si layers.

The resonant frequency of a composite cantilever depends on its dimensions when the materials have been decided. The model used to calculate the resonant frequency was based on a simplified unimorph cantilever with a big proof mass at the free end tip, and only the thicker PZT layer and the Si supporting layer were considered for the calculation. Eq. (1) can be used to calculate the resonant frequency of a unimorph cantilever with a nonpoint proof mass attached at the free end tip [10].

$$f_n = \frac{\upsilon_n^2}{2\pi}\sqrt{\frac{0.236 D_p w}{(l - l_m/2)^3 [m_e + \Delta m]}} \quad (1)$$

$$D_p = \frac{\left[E_p^2 t_p^4 + E_s^2 t_s^4 + 2E_p E_s t_p t_s (2t_p^2 + 2t_s^2 + 3t_p t_s)\right]}{12(E_p t_p + E_s t_s)} \quad (2)$$

$$m_e = 0.236 m w \left(l - \frac{l_m}{2}\right) + m w \frac{l_m}{2} \quad (3)$$

$$m = \rho_p t_p + \rho_s t_s \quad (4)$$

where f_n is the nth mode resonant frequency, υ_n the nth mode eigenvalue, υ_1 = 1.875, w the width of the cantilever beam, l the total length of the cantilever, l_m the length of the proof mass, Δm the mass of the proof mass, D_p a function of the Young's moduli of the two materials, E_p (PZT) and E_s (Si), and their thicknesses, t_p, and t_s, m_e the effective mass of the cantilever beam at the middle of the proof mass [12], m the mass per unit area of the cantilever beam without the proof mass, and ρ_p and ρ_s, respectively, the densities of the piezoelectric material PZT and the supporting layer material Si. Young's modulus of PZT film used for the calculation was determined by nanoindentation [13].

3. Experiment

3.1. Fabrication

The MEMS fabrication process mainly consists of thin film deposition and etching with patterns. An inductive coupled plasma reactive ion etching (ICP RIE) system for anisotropic etching was used to etch out all layers and to release the cantilever beam with the Si proof mass. A Si supporting layer under the cantilever beam is necessary to withstand the internal stress and to improve the mechanical strength of the beam. The thickness of this Si supporting layer is the key factor deciding the resonant frequency of a device when other dimensions are fixed because the resonant frequency is highly sensitive to the thickness of a cantilever beam. However, it is hard to precisely control the thickness of the Si supporting layer and to balance the etching rate and uniformity during the Si etching by the RIE process. The whole fabrication process was therefore started based on a silicon-on-insulator (SOI) wafer, and the buried SiO_2 layer was used as an etching stop layer.

Four masks were used in the fabrication of MEMS PZT cantilever with a proof mass. The fabrication process began with a 100 mm

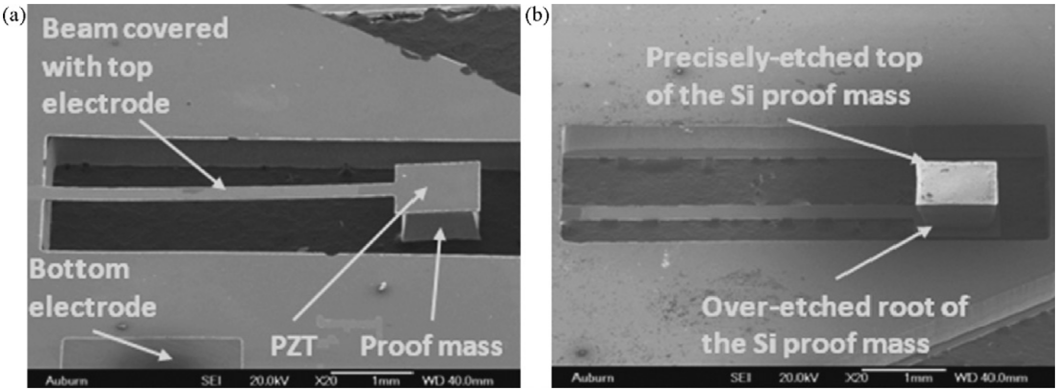

Fig. 2. The SEM pictures of a cantilever (a) front and (b) back side 45° view fabricated on a SOI wafer.

SOI wafer. The thicknesses of the first silicon layer, the thermal silicon dioxide layer, and the second silicon layer are, respectively, 20 μm, 500 nm, and 450 μm. A layer about 500 nm thick of SiO_2 was grown on both sides of the SOI wafer by a wet O_2 method. The silicon dioxide on the front surface will be used to balance the inertial stress of the PZT film, and the one on the back-side surface could be used to mask areas of the surface to prevent damage during the back-side etching. Interlayer Ti (10 nm) and bottom electrode Pt (120 nm) were deposited sequentially by magnetron sputtering without breaking the vacuum. Ti was used for better adhesion between the oxide substrate and the bottom electrode Pt. In total, 12 layers of PZT were coated by sol–gel method to reach the thickness of 1 μm. Each layer was pyrolyzed for 10 min at 350 °C, and every third layer was annealed for 15 min at 650 °C. The top electrode was obtained by a liftoff process after Pt deposition on a layer of photo resist (PR) patterned by the first mask. With the protection of a thick layer of PR patterned by the second mask, the areas around the PZT cantilever structures were etched by RIE until they bared bottom electrode windows for easy access during wire bonding. After covering the areas of the cantilever structure and bottom electrode windows by another layer of PR patterned by the third mask, the areas around the PZT cantilever structures were etched by RIE until the buried SiO_2 layer of the SOI wafer was removed and the cantilever beam was then completely defined. The back-side proof mass was patterned by the fourth mask and the areas without needing etching protected by a layer of PR. A $Pt/PZT/Pt/Ti/SiO_2/Si/SiO_2$ multilayer cantilever structure with an integrated silicon proof mass was finally released after back side SiO_2 and Si RIEs.

3.2. Measurement

The fabricated devices were cleaned, wire bonded, and evaluated. The dimensions and the morphology of the cantilevers were measured using SEM (JEOL 7000 FE). The polarization-electric field hysteresis loop and the resonant frequency were measured using a TF Analyzer 2000 (aixACCT Systems) and an impedance analyzer (Agilent Technologies, 4294A). The output behavior of the device was evaluated using an experimental setup described previously [3]. The device was mounted on an electromagnetic shaker. The vibration frequency and acceleration amplitude were controlled by a function generator and an amplifier, and the simultaneous acceleration amplitude was monitored by an accelerometer mounted on the shaker. A resistive load was connected with the device, and the voltage measured across the resistive load was recorded by an oscilloscope. A sine wave signal was generated by the function generator used as a vibration source. The output voltages of the device at different vibration accelerations, different vibration frequencies, and different resistive loads were then systematically measured. The amplitudes of the output AC voltages were recorded and the corresponding output average powers were calculated.

4. Results and discussion

Fig. 2 shows the 45° view of the fabricated cantilever taken from (a) the front and (b) the back side by SEM. From Fig. 2(a) we can see that the clearly defined straight cantilever beam is slightly bending up due to residual tensile stress in the PZT film. It is hard to completely eliminate the internal stress in such a long cantilever, and the small curvature of the beam has demonstrated the practicable layer structure of the device and the fabrication process. The top of the proof mass, as shown in Fig. 2(b), was more precisely etched when a thin layer of SiO_2 was used as the barrier layer in the back side Si deep etching process. However, the root of the proof mass was slightly over-etched by using the etching condition showing a higher etching rate. The reactive ion etching results from the combination of the effects of physical ion bombardment and chemical ion reaction for improving the etching rate, but the chemical ion reaction increased the isotropic etching at the root areas with a relatively large bombardment pressure. The over-etched root can be mitigated by slowing the etching rate. The undersized proof mass will decrease the resonant frequency of the cantilever and should be considered during designing if it is not completely evitable.

The designed and measured dimensions and calculated volumes of the device are listed in Table 1. The volume is the sum of the volume of the cantilever beam and the volume of the proof mass. It has been decreased by 23% due to the undersized proof mass. The measured width and length of the proof mass are averaged values because the proof mass is not a uniform cuboid. The length of the cantilever beam without the proof mass was also elongated in consideration of the shrinkage of the proof mass. The measured width of the cantilever beam and the thickness of the PZT layer are exactly consistent with the designed value. The thickness of the silicon supporting layer is about 1 μm thicker due to the other layers, such as

Table 1
Dimensions of the cantilever (μm).

	l_p	w_p	t_p	t_s	l_m	w_m	h_m	Volume (mm^3)
Designed	3200	400	1	20	1600	1200	500	0.9984
Measured	3293	400	1.2	21	1415	1015	506	0.7690

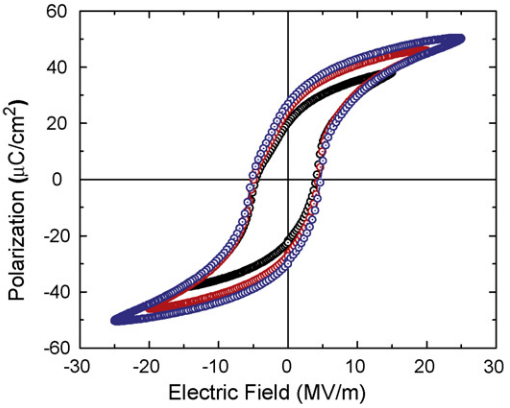

Fig. 3. Piezoelectric hysteresis loop measured from the wire-bonded PZT cantilever device.

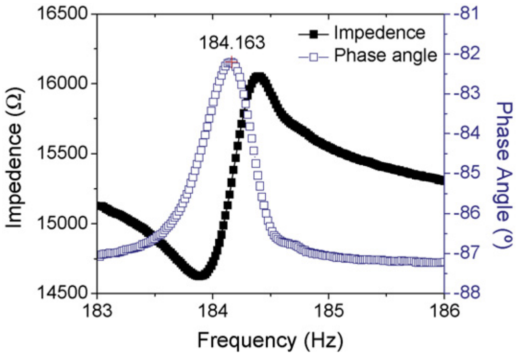

Fig. 4. Measured resonant frequency of the PZT cantilever device.

SiO_2, and Ti/Pt. The undersized proof mass will result in a higher resonant frequency; however, the SOI wafer has almost eliminated the gap between the designed and experimental thickness of silicon layer, and this will highly decrease the difference between the designed and the experimental resonant frequencies of the device.

Fig. 3 presents the measured polarization versus the electric field hysteresis loops of the PZT cantilever device at 15 V, 20 V, and 25 V amplitudes of applied voltage after wire bonding. The remnant polarization is 28.45 μC/cm^2 at an electric field of 25 MV/m and the coercive filed is about 4.95 MV/m at the same electric field. These values are similar to the values measured before wire bonding. The high saturation polarization and low coercive field show that the PZT film retained excellent properties even after the long fabrication process.

The measured impedance and phase angle of the PZT cantilever versus the exciting frequency are shown in Fig. 4. The resonant peak from the phase angle is 184.16 Hz. The *Q*-value of the device is measured to be about 307. This is higher than the designed value, 142 Hz, mainly due to the undersized proof mass. However, this difference (30%) has dramatically decreased compared to the difference (230%) reported in [10], where the PZT cantilever was fabricated based on a Si wafer and the thickness of the supporting silicon layer was hard to precisely control due to an inconsistent RIE process. The calculated resonant frequency by Eq. (1) using the measured dimensions shown in Table 1 is about 176.66 Hz, a difference of about 4.25% from the measured value. This discrepancy is mainly attributed to the modeling, which simplified a multilayer structure to a two-layer structure and assumed perfect adhesion between layers, and the measurement errors of the physical dimensions of the cantilever, especially on the thickness, which is critical to the resonant frequency. In addition, the slight bending of cantilever from the residual stress can be considered to deviate from the expected resonant frequency. According to these results, it is possible to control the resonant frequency of a PZT cantilever with a big proof mass as long as the back side etching parameters are fixed and the dimension change of the proof mass during the process is known.

The *Q*-factor of this cantilever calculated from the phase angle curve in Fig. 4 is about 398, which is much higher than the cantilever with the similar dimensions based on a Si wafer reported in [10]. A higher *Q*-factor device generally has a higher amplitude at the resonant frequency and a lower energy loss, which is desirable for an energy converter. However, a higher *Q*-factor device also means that its response falls off more rapidly when the frequency deviates from the resonance. This high sensitivity to the vibration frequency is a demerit for energy harvesting devices because small deviations of the vibration frequency from the device's resonant frequency will induce significant reduction of the output power. A lower *Q*-factor will be preferred as long as the output power is high enough to support the application requirements.

The measured peak voltage and the calculated average power versus resistive load at 0.50*g* and 0.75*g* accelerations and measured corresponding resonant frequencies, 184.0 Hz and 183.8 Hz are shown in Fig. 5. The peak voltage increases with the increasing resistive load, and the average power shows a maximum value at a certain resistive load, which is named the optimal resistive load. The measured optimal resistive loads for these two conditions are both 16 kΩ, where the maximum average powers are individually 0.24 μW and 0.32 μW, and the corresponding peak voltages are 88 mV and 101 mV. The output current is an important parameter for a power-generating device because the electronic components for power conversion consume an electric current. The output peak current was calculated and its relationships with the peak voltage and average power were shown in Fig. 6. The optimal output peak currents of this device at 0.50*g* and 0.75*g* acceleration amplitudes are 5.52 μA and 6.31 μA, respectively. Such values show the potential for miniaturized devices. An integrated voltage multiplier was

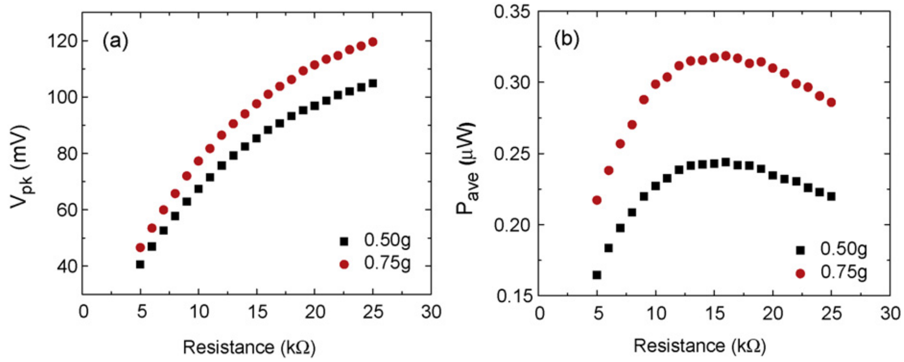

Fig. 5. (a) Peak voltage and (b) average power versus resistive load at 0.50*g* and 0.75*g* accelerations.

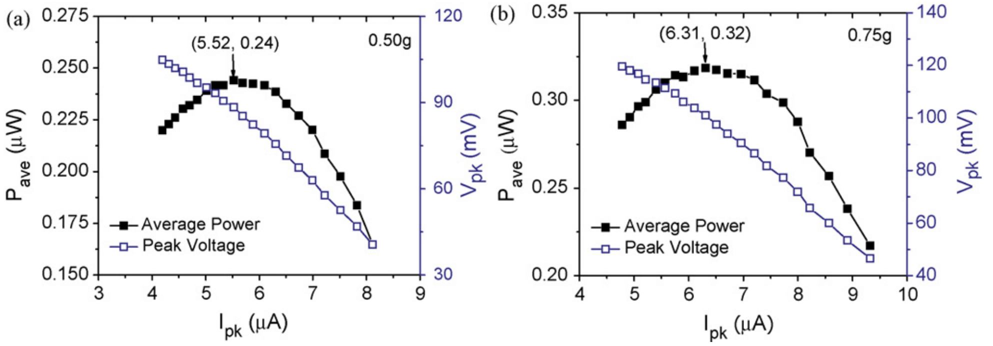

Fig. 6. Peak voltage and average power versus current at (a) 0.50*g* and (b) 0.75*g* accelerations.

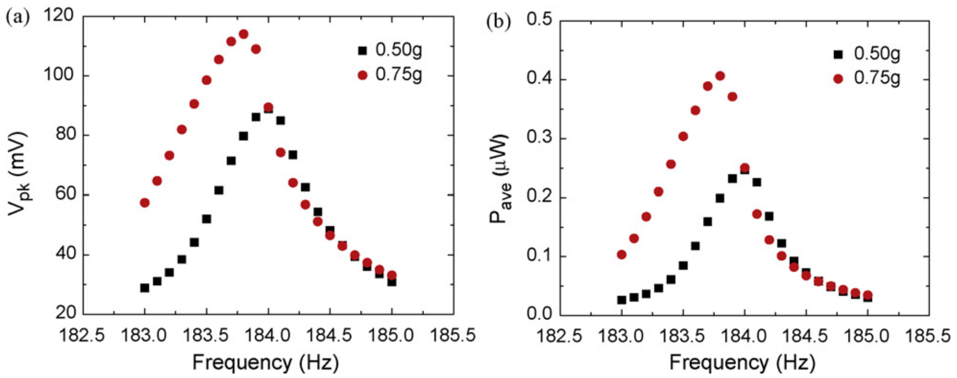

Fig. 7. (a) Peak voltage and (b) average power vs. exciting vibration frequency at 0.50*g* and 0.75*g* accelerations.

reported to boost up the energy generated by the device to store in a supercapacitor and to use to supply power to an electronic device having a short period of activity [4]. Fig. 7 presents the output voltage amplitude and the average power generated on the optimal resistive load versus the vibration frequency at 0.50*g* and 0.75*g* acceleration amplitudes. The *Q*-factor of the device relates to the sharpness of the plot, that is, the frequency range where the device could be utilized. The higher *Q*-factor of this device as compared with the device reported in [10] corresponds to a narrower applicable frequency range, but the energy loss of this device is smaller. We can also see that the resonant frequencies, the peak frequencies in Fig. 7, at 0.50*g* and 0.75*g* acceleration amplitudes are 184.0 Hz and 183.8 Hz, respectively. The apparent shift of the resonant frequency to a lower value with increasing exciting vibration amplitude is mainly attributed to the increasing elastic compliance of PZT resulting from nonlinear effects under large stress [10].

5. Conclusions

A MEMS PZT cantilever with an integrated Si proof mass is designed and fabricated on a SOI wafer, and a Pt/PZT/Pt/Ti/SiO_2/Si/SiO_2 multilayer device is generated for low frequency vibration energy harvesting. The integrated Si proof mass at the free end tip of the cantilever is used to decrease the resonant frequency of the device. The SiO_2 layer in the SOI wafer is used to precisely control the thickness of the silicon supporting layer in the cantilever beam because thickness is the most sensitive factor impacting the resonant frequency. The thin film PZT generated by sol–gel has a thickness of around 1.0 μm. The fabricated power generator has a beam dimension of 4800 μm × 400 μm × 22 μm and a proof mass dimension of around 1415 μm × 1015 μm × 506 μm. The entire effective volume (beam and mass) is about 0.7690 mm^3. When excited at 0.75*g* ($g = 9.81\ m/s^2$) acceleration at its resonant frequency of 183.8 Hz, the AC output measured across a resistive load of 16 kΩ connecting to the device in parallel has an amplitude of 101 mV. The calculated average power and power density at the same measurement conditions are, respectively, 0.32 μW and 416 $\mu W/cm^3$.

Acknowledgements

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Biographies

Dongna Shen received her PhD degree in Materials Engineering from Auburn University Auburn, Alabama, USA, in 2008 and received her BS and MS degrees in Materials Science and Engineering from Beijing University of Technology in Beijing, China, in 2000 and 2003 respectively. She is currently working on CdTe thin film solar cells in Electrical Engineering at the University of South Florida. Her main research interests involve energy harvesting or conversion systems, piezoelectric thin films, piezoelectric sensors and actuators, and CdTe thin film solar cells.

Jung-Hyun Park is currently a PhD degree student in Materials Engineering at Auburn University, Auburn, Alabama, USA. He received his BS degree in Metallurgical Engineering from In-ha University, Incheon, Korea, and MS degree from Auburn University with the subject of cryogenic sputter deposition of low melting temperature materials. His fields of interest include integrated piezoelectric film on micro transducer, MEMS process development and energy harvesting devices.

Joo Hyon Noh received his MS and PhD degrees from Yonsei University, Seoul, South Korea, in 2000 and 2008, respectively. In 2008, he worked as a postdoctoral researcher in Materials Engineering at Auburn University. Currently, he works as a postdoctoral researcher in the Department of Materials Science and Engineering, University of Tennessee, Knoxville. His research is focused on smart materials, such as gas sensitive oxide materials, for functional applications.

Song-Yul Choe, an associate professor in the Mechanical Engineering Department at Auburn University, earned his PhD in Electrical Engineering from the Technical University of Berlin in 1991. Before joining the Mechanical Engineering Department, he was a program manager and research professor at the Center for Advanced Vehicular Systems at Mississippi State University in Starkville, Mississippi, and led the efforts on the fuel cell and the advanced intelligent vehicle projects. From 1996 to 2001, he worked as a director overseeing advanced automotive technology at Hyundai Corporation, including research and development of alternative power trains such as ICE based hybrid systems and PEM fuel cell systems.

Seung-Hyun Kim is vice president of INOSTEK INC. and is the head of its Research and Development Center. He has been active in ferroelectric and piezoelectric thin films for electronic devices for the last 20 years. He worked at MIT from January 2008 to February 2009 when he transferred to Brown University in as a contracted staff/faculty member. Dr. Kim's research interests are in the area of piezoelectric materials development and MEMS processing. Dr. Kim received his Bachelor (1989), Master (1991) and PhD degrees (1996) in Ceramic Engineering from YonSei University, South Korea. From 1997 to 2000, he worked at North Carolina State University on the research staff, and from 2004 to 2006, he served as an adjunct professor of physics at Kookmin University in Korea. Dr. Kim's educational and academic activities cover experimentation and applications of materials and devices.

Howard C. Wikle, **III**, received his BS and PhD degrees in Materials Engineering from Auburn University, Auburn, AL, USA, in 1991 and 1998, respectively. In 2007, he joined the Materials Research and Education Center at Auburn University as a research engineer. His research interests are in the areas of smart materials for sensor platforms, conducting polymer transducers and systems integration.

Dong-Joo Kim is currently an associate professor in the Materials Research and Education Center and the Department of Mechanical Engineering at Auburn University. He received his BS and MS degrees in ceramic engineering from Yonsei University, South Korea in 1993 and 1995, respectively. He was awarded a PhD from North Carolina State University in 2001 for work on piezoelectric thin films. Following this, he worked as a postdoctoral researcher at Argonne National Laboratory and joined Auburn University in 2003. Dr. Kim's interests include investigation of smart materials and ceramic films for sensors and actuators applications.