Piezoelectric MEMS for energy harvesting

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Abstract. Recently, piezoelectric MEMS have been intensively investigated to create new functional microdevices, and some of them have already been commercialized such as MEMS gyro sensors or miropumps of inkjet printer head. Piezoelectric energy harvesting is considered to be one of the promising future applications of piezoelectric MEMS. In this report, we introduce the deposition of the piezoelectric PZT thin films as well as lead-free KNN thin films. We fabricated piezoelectric energy harvesters of PZT and KNN thin films deposited on stainless steel cantilevers and compared their power generation performance.

1. Introduction
Recently, multifunctionality of ferroelectric materials have attracted attention in the field of microelectromechanical systems (MEMS) because they can give new and superior sensing or actuating performances by integrating ferroelectric thin films into the simple micro-structures. Among a variety of functionality in ferroelectric materials, piezoelectricity is the most important properties for the sensors and actuators in MEMS because the piezoelectric materials have superior electromechanical coupling characteristics. In order to integrate piezoelectric materials into MEMS, the piezoelectric materials should be prepared in thin-film form to be microfabricated by photolithography. The most popular piezoelectric materials are Pb(Zr,Ti)O3 (PZT), and the deposition and characterization of PZT thin films have been intensively studied. Recently, some of piezoelectric MEMS composed of PZT films have been developed as commercial products, such as micropumps of inkjet printer heads or MEMS gyro sensors. Vibration energy harvesters (EHs) is one of the promising applications in piezoelectric MEMS because piezoelectric thin films enable to generate relatively large electric power by making the simple micro- or millimeter-scale unimorph cantilevers. However, to develop the high energy efficient and reliable piezoelectric MEMS EHs, several technical issues still remain; deposition of the well-crystallized piezoelectric thin films, and furthermore, precise measurement of piezoelectric properties of thin films. Environmental impact of lead in PZT is also a serious problem for the practical use of the piezoelectric MEMS, and the lead-free piezoelectric ceramics including thin films have been investigated intensively.

2. Deposition of piezoelectric PZT thin films
In the piezoelectric MEMS, PZT-based ferroelectric thin films are the most popular materials used because of their large piezoelectric properties compared with non-ferroelectric thin films such as AlN or ZnO. The required specification of the deposition of the PZT thin films are 1) thickness more than 1 μm, 2) uniformity of the film-thickness on large Si wafers (> 6 inches), 3) low-cost and high deposition rate. Several methods have been studied such as chemical solution deposition (CSD; sol-gel deposition), chemical vapor deposition (CVD), pulsed laser deposition (PLD), and rf-sputtering. Those methods can
produce well-crystallized PZT thin films with high piezoelectric coefficient, however, each of them has advantage and disadvantage, especially from the viewpoint of mass-production of piezoelectric MEMS. CVD is another candidate for PZT deposition. This method has advantage for the excellent step coverage which is strongly required for semiconductor memories (FeRAM). However, the source materials of PZT are relatively expensive so that it is not suitable for the deposition of micrometer-thick PZT films. PLD is also a popular method for high-quality PZT deposition. The main drawback of PLD is the deposition area with uniform thickness by the conventional PLD was as small as a square centimeter, however, the PLD system for mass production has recently developed. CSD and rf-sputtering are the most popular deposition processes of the PZT thin films for MEMS applications. CSD method can produce PZT thin films without expensive deposition apparatus such as vacuum system. However, the thickness of the layer by single spin coating is typically as thin as ~0.1 μm, and the thick PZT films more than 1 μm needs multi-spin coating with each pre-baking process. Therefore, the repetition of spin coating and baking processes needs long time to accomplish the total deposition. On the other hand, rf-magnetron sputtering is a practical deposition method of PZT films on large Si wafers with high deposition rate more than 1 μm/h. Initial cost of the sputtering apparatus is expensive, however, the cost of the sputtering targets is lower than the other deposition methods. If the deposition condition is optimized, high-quality PZT thin films can be stably produced on a variety of substrates. Recently lead-free piezoelectric materials have been intensively studied to mitigate environmental impact of the piezoelectric devices. A variety of lead-free piezoelectric materials such as BaTiO\(_3\) (BT), (Bi,Na)TiO\(_3\) (BNT), and BiFeO\(_3\), (K,Na)NbO\(_3\) (KNN) have been studied. Among these lead-free materials, KNN shows the highest piezoelectric properties and their Curie temperature is also comparable with those of PZT. For the lead-free piezoelectric MEMS, we have successfully prepared KNN thin films on Si substrates by rf-magnetron sputtering and demonstrated that the KNN thin films have large piezoelectric properties comparable with the PZT thin films [1].

3. Lead-free piezoelectric thin-film EHs of stainless-steel cantilevers

3.1. Fabrication process of piezoelectric thin-film EHs
Piezoelectric MEMS EHs usually have simple unimorph cantilever structures composed of piezoelectric PZT thin films on Si substrates. In order to maximize the vibration amplitude, the resonance frequency of the cantilevers should be adjusted to environmental vibrations. Considering the brittleness of Si-based unimorph cantilevers, the fatal damages such as cracking or breaking of the cantilever are inevitable under the continuous and unregulated vibration. Furthermore, the resonance frequency of conventional MEMS EHs is usually more than 1 kHz because of the small size of the resonators, although the frequency of environmental vibrations is generally less than 200 Hz. In order to solve these issues, we fabricated piezoelectric thin-film EHs using thin metal cantilevers to improve the toughness of the
resonators. The fracture toughness $K_{Ic}$ of stainless steel is more than fifty times larger than that of Si. Therefore, the resonance frequency can be easily reduced even with the heavy tip mass on the thin cantilevers.

We deposited both of PZT and lead-free (K,Na)NbO$_3$ (KNN) thin films on the microfabricated metal cantilevers by rf-magnetron sputtering and compared their power generation performance as piezoelectric MEMS energy harvesters. The fabrication process is shown in Fig. 1. First, a photosist pattern was formed on both sides of a 300-µm-thick stainless steel (SS430) plate to prepare the cantilever structure with tip mass and fixed end. After that, a two-step spray etching process was conducted using ferric chloride solution and 30-µm-thick cantilevers were fabricated. The thickness of the tip mass and fixed end was 300 µm. Prior to PZT or KNN deposition, Pt/Ti bottom electrodes were deposited on the cantilevers. Successively, the PZT and KNN thin films were deposited by rf-magnetron sputtering onto the Pt/Ti-coated cantilevers. During the deposition of the piezoelectric thin films, the cantilevers were heated up to around 650°C, and a mixed gas Ar/O$_2$ was introduced into sputtering chamber. The thickness of the PZT and KNN films was 2.0–2.5 µm. Finally the Pt top electrodes were deposited through a shadow mask. Direct deposition of the piezoelectric thin films on the microfabricated cantilever could simplify the fabrication of the piezoelectric MEMS EHs. Fig. 2 shows images of the piezoelectric EHs with the KNN thin films on stainless steel cantilevers. We could obtain the flat unimorph cantilevers.
3.2. Power generation characteristics
We examined the power generation performance of the PZT and KNN MEMS-EHs with the same dimensions of the cantilever (length: 7.5 mm, width: 5 mm) [2]. We mounted the EHs on the vibration exciter, and the top and bottom electrodes of the piezoelectric thin films were connected to a load resistance. Fig. 3 shows the frequency response of output voltage of PZT thin-film EHs in an open circuit state at the acceleration of 10 m/s². A clear peak of the output voltage appeared at a resonance frequency of 367 Hz, and the Q value was measured as 80 by the half-power bandwidth method. In addition, the non-linear vibration due to the softening spring effect was observed. This non-linear resonance is attributed to large deflection of the thin stainless steel cantilever at the resonance. Similar non-linear vibration was observed for KNN thin-film EHs.

Fig. 4 shows the output voltage and power of PZT- and KNN-EHs as a function of load resistance. The measurement was performed at the resonance frequency under the acceleration of 10 m/s². The averaged output power of the PZT-EHs reached 6.7 µW at the optimum load resistance of 10 kΩ, while those of the KNN-EHs were 1.6 µW and 5 kΩ, respectively. Comparison of the KNN and PZT EHs is listed on Table 1. The generalized electromechanical coupling factor of $K^2$ was derived by the theoretical calculation [3]. The output power as well as $K^2$ of KNN-EHs were lower than those of the PZT-EHs in this experiment. Lower output power of KNN-EHs is attributed by large dielectric loss (tanδ) of the KNN thin films on stainless cantilevers. It means that the optimization of the deposition condition of the KNN thin films on the stainless steel would improve the output performance.

4. Summary
Piezoelectric thin films have been started to be used in the practical MEMS applications, and the progress of the deposition process and measurement technologies improve the piezoelectric properties and their stability of the thin films. EHs are one of the promising applications of piezoelectric MEMS which would enable small-size EHs with high efficiency. We fabricated piezoelectric thin-film EHs using stainless steel cantilevers and evaluated their power generation efficiency. PZT and lead-free KNN thin films were directly deposited on the microfabricated stainless-steel cantilevers by rfsputtering, and we confirmed that the high energy efficiency as well as excellent toughness under the large vibration.

References
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