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Vibrational micro-energy harvesters utilizing Nb-doped $Pb(Zr,Ti)O_3$ films on stainless steel substrates

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Abstract. This work presents the micromachined energy harvesters using Nb-doped $Pb(Zr,Ti)O_3$ (PNZT) films grown directly on the stainless steel substrates (SUS430). Piezoelectric materials on metallic substrates have been attracted to practical and robust energy harvesters. Nb-doped PZT films with (001)-preferred orientation grown on SUS substrates provided excellent properties for energy harvesting – high piezoelectric coefficient (e_{31} = -10.6 C/m^2) and low dielectric permittivity (ε_r = 373). The PNZT-based micro-energy harvester comprising a cantilever of 1.7 mm×5 mm ×0.05 mm and a proof mass of 3 mm×5 mm × 0.47 mm achieved the normalized power density (NPD) of 2.87 mW.g^{-2}.cm^{-3}. It is the highest performance among the published SUS-based energy harvesters, being closer to the best Si-based energy harvesters.

1. Introduction

Vibrational energy harvesters providing electrical power supply to wireless sensor nodes have become compelling issues. Energy harvesters have been developed from piezoelectric materials grown on silicon substrates [1-3]. The silicon-based energy harvesters have achieved substantial progress in term of output power density [1,2]. Minh *et al.* developed the high performance piezoelectric micro-energy harvesters that piezoelectric films grown directly on Si substrates [1,2]. The lead-free (Mg,Zr)-doped AlN based micro-energy harvesters provided the NPD at level of 4 mW.g^{-2}.cm^{-3}[1]. However, from practical perspectives of many applications, silicon-based energy harvesters have to face the robustness when exploiting ambient vibrations in low frequency region. Working in low frequency and magnitude vibrations requires that structural materials are capable of carrying heavy weight. Metallic substrates that excel in mechanical properties such as large fracture toughness and high elastic strain limit provide viable solution to the issue. Unfortunately, low piezoelectricity on metallic substrates and difficulties in micromachining contribute to low performance of metal-based energy harvesters [4-7]. Cao *et al.* had used AlN grown on SUS to fabricate piezoelectric macro-energy harvesters with the NPD of 40-400 μW.g^{-2}.cm^{-3} [5,6]. These performances are much lower than those of Si-based harvesters. To address the problems, in this work, we developed the piezoelectric micro-energy harvesters that exploited the highly piezoelectric Nb-doped PZT films grown directly on SUS substrate and utilized electrochemical technique for micro-machining the metallic substrates.

2. Fabrication of Nb-doped PZT/SUS based micro-energy harvesters

PNZT films were deposited on SUS substrates with Ir/Ti seed layer by an RF sputter (Model STV4320, Shinko Seiki) with Ar/O_2 gasses and $Pb_{1.3}(Zr_{0.46}Ti_{0.42}Nb_{0.12})O_3$ target. PNZT films were synthesized at the condition – RF power of 200 W, gas pressure of 0.5 Pa with Ar + 2.5% O_2, and substrate temperature of 525 ^{o}C [8]. Figure 1 shows X-ray diffraction patterns of the as-deposited PNZT films. The films had highly preferred (001)-PNZT orientation. PNZT films provided high piezoelectric coefficient of 10.6 [8] and low dielectric permittivity of 373. Therefore, we exploited these attractive properties to develop energy harvesters.

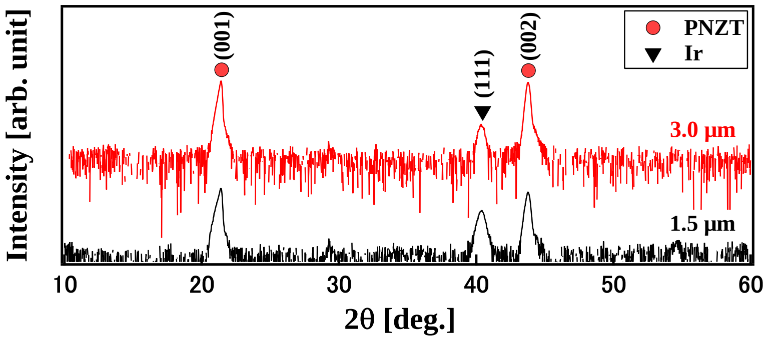

Figure 1. X-ray diffraction patterns: PNZT films on SUS of 1.5 μm (black), and 3 μm (red).

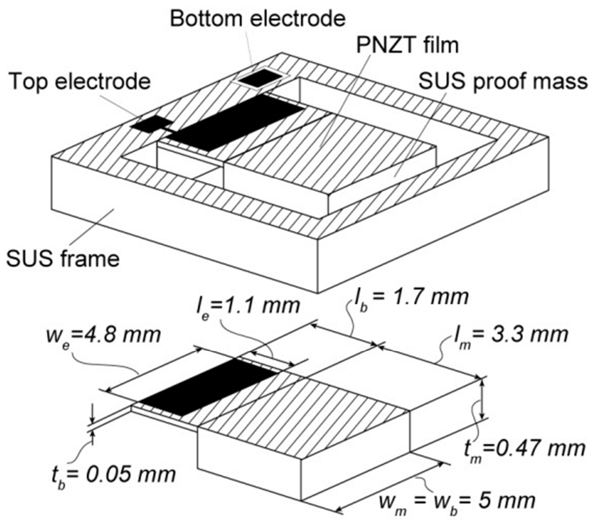

Figure 2. Illustration of PNZT/SUS based micro energy harvester with the geometric parameters.

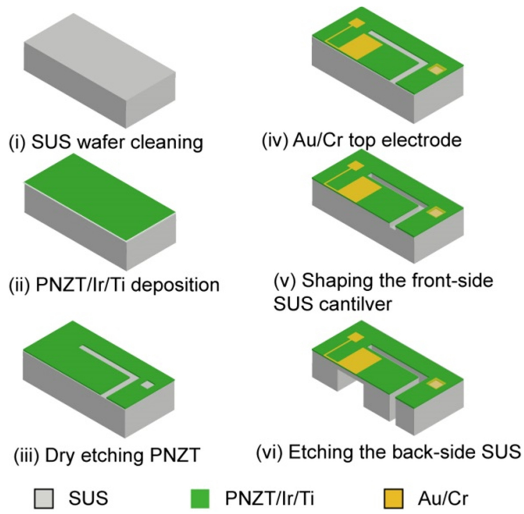

Figure 3. Fabrication flow of PNZT/SUS micro-energy harvesters.

The 3-μm PNZT films on SUS430 substrates of 470 μm were utilized for fabricating the energy harvesters that were composed of a cantilever and a proof mass. The geometric parameters of the harvesters are presented in figure 2. The fabrication flow is presented in figure 3. At first, PNZT film was etched to form a piezoelectric element on the cantilever by using fast atomic beam (FAB) etching technique with SF_6 gas (Figure 3 (ii)). The PNZT etching rate was 14 nm/min on average under the same condition as that in our previous study [2]. Next, Au(200 nm)/Cr(10 nm) thin films were deposited on the wafer and were etched by Au and Cr wet etchants, respectively, to form the top electrode and the open contact window (Figure 3 (iii)). In order to form the SUS cantilever, we etched SUS from the front-side wafers by H_3PO_4-based electrochemical etching (Figure 3(iv)). The electrochemical setup included an electrolyte of H_3PO_4 (99.8%), a stainless steel cathode, and an anode attached by our wafer. The SUS etching rate was approximately 1.00 μm/min at the applied voltage of 4.5 V and the electrolyte current of 0.4 A. The SUS etching depth was the same as the desired cantilever's thickness. Finally, the backside of the SUS wafer was also electrochemically etched to form the proof mass and the desired SUS cantilever (Figure 3(v)). The photographic and scanning-electron-microscopic images of the fabricated PNZT/SUS energy harvester are exhibited in figure 4.

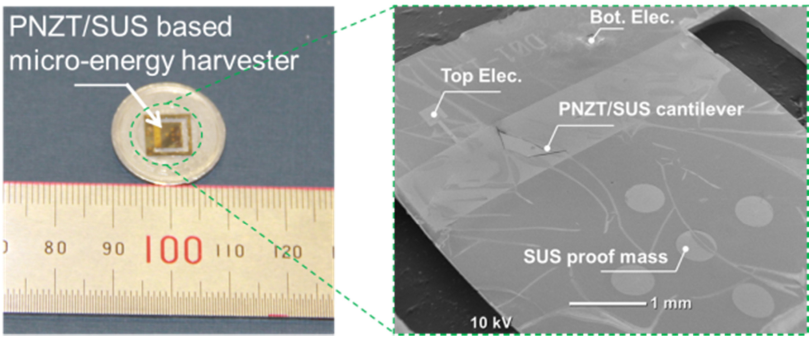

Figure 4. The photographic and scanning electron microscopic (SEM) images of the PNZT/SUS based micro-energy harvester.

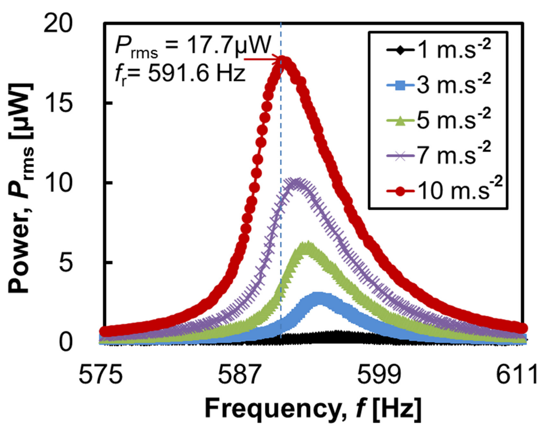

Figure 5. Output power spectra of the PNZT/SUS based micro-energy harvester at the optimal resistance of 49.7 kΩ.

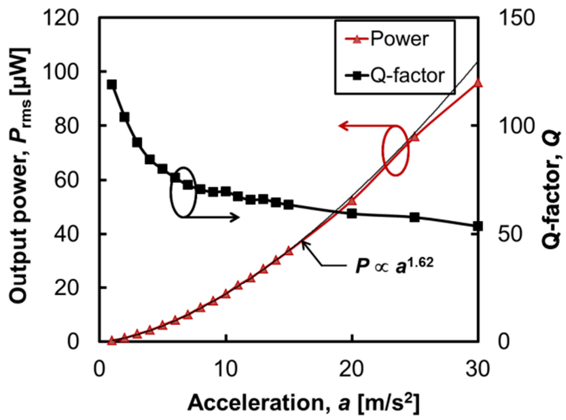

Figure 6. Output power and Q-factor (Q = $f_r/\Delta f$, *Δf is a bandwidth of a power spectrum*) as function of the input acceleration.

3. Results and Discussions

The fabricated PNZT/SUS based energy harvester was evaluated power characteristics using the resistive connection for matching impedance and the shaker for controlling the harmonic acceleration. Figure 5 displays the power spectra of the PNZT/SUS based energy harvester under various accelerations. The harvester had the weakly-softening effect, resonating at 591.6 Hz with the maximum output power of 17.7 µW at the optimal resistance of 49.7 kΩ and the acceleration of 10 m.s^{-2}. For ideal linear harvester, output power is proportional to squared acceleration, a^2. Figure 6 shows that the PNZT/SUS based harvester depended on $a^{1.63}$. When increasing the acceleration, the device had the softening effect and the degraded Q-factor led to lowering the output power. The Q-factor decreased from 120 to 54 when the input acceleration increased from 1 m.s^{-2} to 30 m.s^{-2}. However, the output power achieved up to 96 µW at the acceleration of 30 m.s^{-2} (Figure 6).

For comparison, performance of the state-of-the-art piezoelectric micro-energy harvesters has been expressed on the NPD-frequency graph including the iso-energy contours (Figure 7). The device achieved the NPD of 2.87 mW.g^{-2}.cm^{-3} that was 7-fold those of KNN/SUS harvester and AlN/SUS harvesters [5-7]. And the NPD of PNZT/SUS based harvester is comparable to those of AlN/Si and

KNN/Si based energy harvesters [1,2,9]. This result of this work is superior to those of the metallic energy harvesters and approaches closely towards the best Si-based energy harvesters.

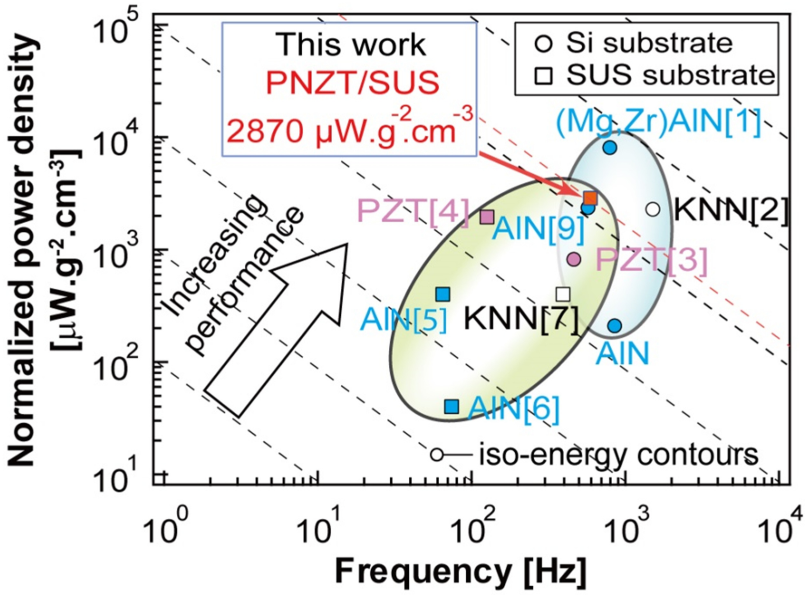

Figure 7. Comparison of the state-of-the-art piezoelectric energy harvesters for both Si- and SUS-based development (g = 9.89 m.s^{-2}).

4. Conclusions

This work presents the Nb-doped PZT/SUS based micro-energy harvester. PNZT films were grown directly on SUS substrates with highly preferred (001) orientation. The micromachining process was established for fabricating PNZT/SUS micro energy harvester. The output power was up to 96 μW at the acceleration of 30 m.s^{-2}. The micromachining harvester was confirmed with the high normalized power density of 2.87 mW.g^{-2}.cm^{-3}. This achievement was 7-fold increase compared to those of KNN/SUS and AlN/SUS based energy harvesters, being comparable to those of KNN/Si and AlN/Si based energy harvesters. The achievement opens a door for high performance micro energy harvesters exploiting piezoelectric films on metallic SUS substrates and leading to practical applications in which energy harvesters based on Si-platforms are impractical.

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