HIGHLY EFFICIENT PIEZOELECTRIC MICRO-ENERGY HARVESTERS WITH ALN THIN FILMS GROWN DIRECTLY ON FLEXIBLE TI FOILS

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ABSTRACT

This work presents the highly efficient, micromachined energy harvester using lead-free piezoelectric AlN thin films grown directly on Ti foils for the first time. 4-µm AlN films with (002)-preferred orientation were grown on 50-µm Ti foils by an AC reactive magnetron sputter with Ar/N_2 gas and Al target. The rocking curve full width at half maximum (FWHM) of the (002)-AlN peak was 2.3°, being comparable with that of polycrystalline AlN thin films grown on Si substrates. Highly (002)-oriented AlN films on Ti foils contributed to the excellent properties – normalized piezoelectric coefficient, $e_{33,\mathrm{eff}}/e_{33,\mathrm{crystal\text{-}AlN}}$ of 99.92 %, relative permittivity, ε_r of 9.36. AlN/Ti-based micro-energy harvesters with the cantilever and the proof mass were fabricated and achieved the high normalized power density (NPD) of 1.45 $mW.g^{-2}.cm^{-3}$. It is the best ever published performance for the environment-friendly energy harvesters developed from metallic substrates.

INTRODUCTION

A miniature electrical power source has been strongly desirable for modern wireless sensor nodes. Harvesting electricity from ambient vibrations by piezoelectric effect becomes a tendency for micro-energy harvesting [1,2]. Piezoelectric energy harvesters are able to realize smart sensor nodes, where the long-time operation, miniaturization, environment-friendly materials take priority [3, 4].

Vibrational energy harvesters providing electrical power supply to wireless sensor nodes have become compelling issues. Energy harvesters have been developed from piezoelectric materials such as PZT, AlN, etc. [3-5]. Since AlN films are lead-free piezoelectric materials and well-developed on Si substrates, their high piezoelectric coefficient and low permittivity have fostered the development of silicon-based micro-energy harvesters [3,6].

From practical perspectives of exploiting ubiquitous ambient vibrations, silicon devices have to face the robustness when operating in the low-frequency region. Metallic platforms are desirable to replace silicon one for not only energy harvesting but also other applications seeking properties – high fracture toughness and elastic strain limit [7-10]. Hence, flexible or high elastic limit materials have been attractive to serve as structural materials in mechanical microdevices in general and energy harvesters in particular [8-10].

Piezoelectric functional materials on Si platforms become well mature and have been applied intensively to both commercial products and research studies as well [1-6,11]. Unfortunately, offering piezoelectricity to flexible substrates is in the initial stage. Previous studies show the large residual stress and the significant degradation of the crystallinity and dielectric and piezoelectric properties of the AlN films grown directly on flexible substrates [7-8]. This results in the low performance of the devices [7-8]. The low properties might be consequences of the different thermal coefficients, the lattice mismatch, and the diffusions from substrate elements to piezoelectric films.

To address these problems, we developed free-stress and highly crystalline AlN films on Ti foils. Then, AlN/Ti materials were utilized for developing micromachined energy harvesters. In addition, we present the highly efficient, micromachined energy harvester using lead-free piezoelectric AlN thin films grown directly on Ti foils. The AlN film deposition and the device fabrication and evaluation were presented in this work.

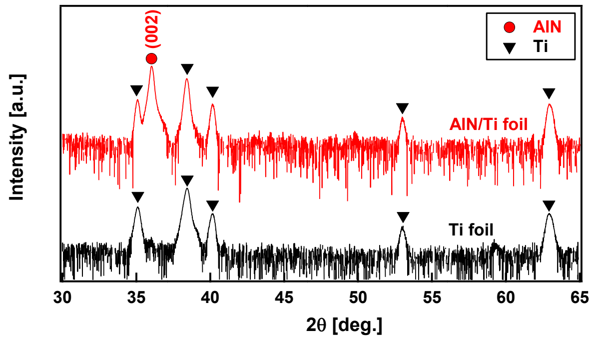

Figure 1: XRD θ/2θ patterns: as-deposited 2 µm AlN films (a), Ti foils (b)

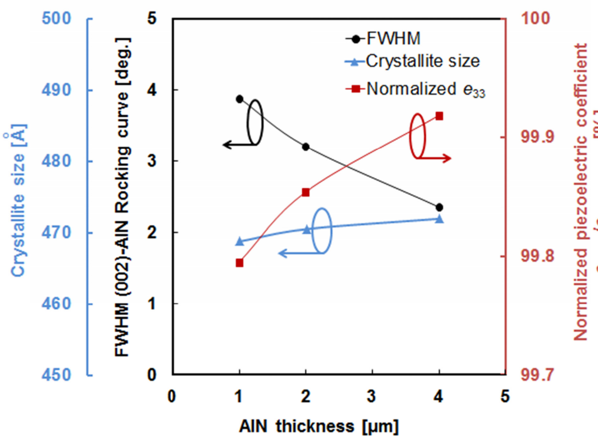

Figure 2: Crystallite size (dark blue), FWHM (002)-AlN Rocking scan (black) and normalized piezoelectric coefficient e_{33}(red) as a function of the thickness of AlN films grown directly on Ti foils.

ALN FILMS GROWN DIRECTLY ON TI FOILS

Polished Ti foils with 50 µm in thick served as substrates for growing AlN films. AlN films were deposited by an alternative current (AC) magnetron reactive sputter (Model AM212-1-S) with the Ar/N_2 gasses and the Al target. AlN films were synthesized at the condition – an AC power of 3 kW, a gas pressure of 0.5 Pa with the Ar/N_2 (1:3.1) flow rate ratio.

The crystallinity of as-deposited 2µm-AlN films was investigated by θ/2θ and Rocking curve scans with an X-ray diffractometer (XRD) (Bruker D8). Figure 1 displays θ/2θ XRD patterns of the as-deposited AlN films. The films had highly preferred (002) orientation. The (002) peak locates at 36.039°. The average crystallite size was approximately 47 nm by the Scherrer method.

The previous studies point out that the smaller full width at half maximum (FWHM) of the (002) Rocking curve scan is preferable for high piezoelectricity [11]. Figure 2 show the FWHM values and normalized piezoelectric coefficient depended on the AlN thickness grown directly on Ti foils. Increasing the AlN thickness leads to lower the FWHM; therefore the higher piezoelectric coefficient was achieved.

FABRICATION OF THE ALN/SUS-BASED MICROENERGY HARVESTERS

To demonstrate the potential application of our AlN films grown on Ti foils, we developed the first prototype microenergy harvesters that composed of an AlN/Ti cantilever and a Cu proof mass. Figure 3 shows the detail geometric parameters.

The harvesters consisted of the AlN/Ti cantilever and the Cu proof mass. The micro-fabrication flow was established from the developed AlN/Ti, wet etching for AlN, and HF-based wet etching for Ti foils, and H_3PO_4-based electrochemical etching for Cu wafers. (Fig. 4).

At first, 4 µm AlN films on Ti foils were utilized for fabricating micro-energy harvesters (Fig. 4 (i)&(ii)). AlN films on Ti foils were formed a piezoelectric element on the cantilever and a contact window for the bottom electrode (Fig. 4 (iii)). The AlN etching rate was 130 nm/min by TMAH 2.63% at the temperature of 35 °C. 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 contact pad for the bottom electrode (Fig. 4 (iv)). In the meanwhile, Cu wafer with 0.47 mm was electrochemically etched by the HP_3O_4-based electrolyte for serving as the proof mass. The Ti 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 front-side Cu wafer was etched with a certain thickness (Fig. 4 (v)), then aligned and bonded to the Ti wafer by adhesive (Fig. 4 (vi)). The Ti cantilever was etched by the HF-based etchant at the room temperature with the etching rate of 800 nm/min (Fig. 4 (vii)). Finally, electrically etching the backside Cu wafer is to achieve the harvesters (Fig. 4 (viii)).

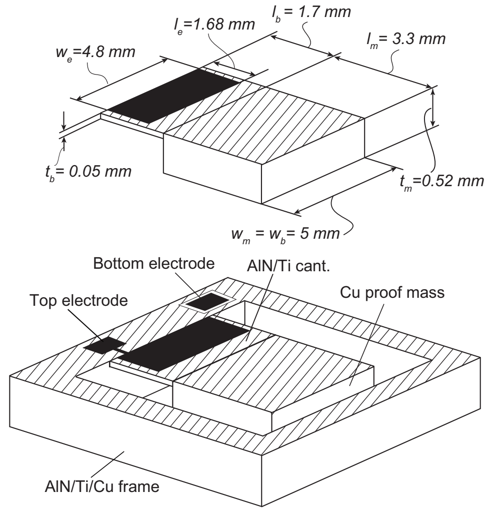

Figure 3: The illustrative structure and the geometric parameters of AlN/Ti-based energy harvesters

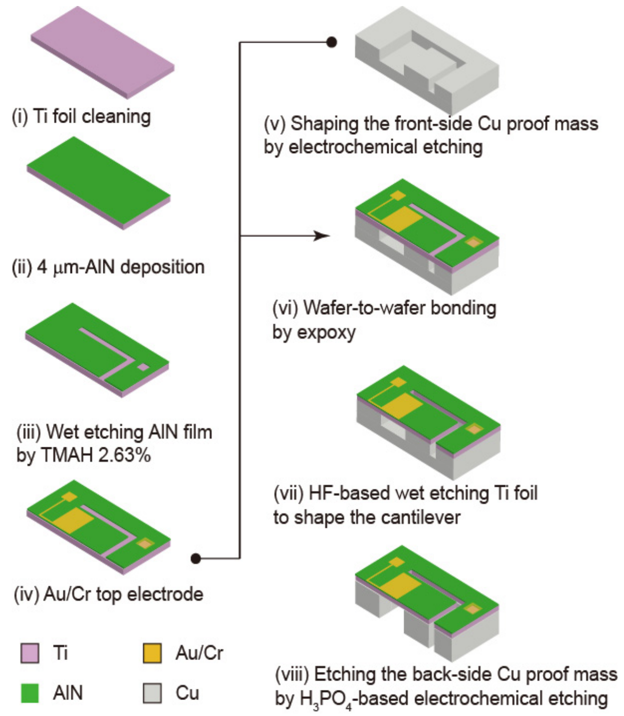

Figure 4: The fabrication flow of AlN/Ti based energy harvesters

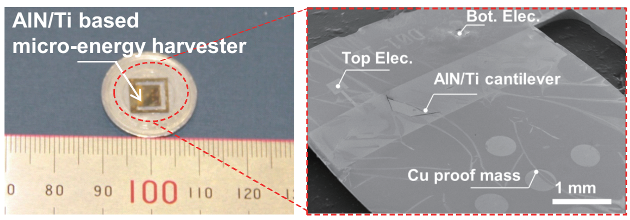

Figure 5: The photographic and electron scanning microscopic images of the harvester.

In this paper, the first prototype device with the overall cantilever size was 5 mm × 5 mm × 0.52 mm. Figure 5 exhibits the harvester photography embedded with the electron scanning microscopic image.

DEVICE EVALUATION AND DISCUSSION

The AlN/Ti based harvester was evaluated by applying the controllable vibration source from a shaker (Asahi Seisakusyo: APD-200FCG). The tunable resistor was connected to the device for impedance matching. Figure 6 shows the power spectrum of the harvester at the input acceleration of 10 m/s^2. The maximum output power was 13.1 µW. The device resonated at the frequency of 645.3 Hz. The Q factor, defined as the ratio between the resonant frequency and the FWHM of the spectrum, was 248. It is comparable to AlN/Si-based energy harvesters[4,6]. However, it is about two times lower than that of the doped AlN/Si-based harvesters [3].

Figure 7 shows the output voltage, current, and power depend on the load resistance. The device had the optimal resistance of 1.4 MΩ. The high optimal resistance is originated from the lower permittivity of AlN material. AlN grown on Ti foils had the permittivity of 9.36 that is consistent with those of polycrystalline AlN films grown Si. The pseudo open-circuit voltage and pseudo short-circuit current were 4.8 V and 4.0 µA, respectively. With the output power of 13.1 µW, the device achieved the normalized power density (NPD) of 1.494 $mW.g^{-2}.cm^{-3}$. The NPD is defined as the output power divided the effective volume and the square of the input acceleration[3,4]. The effective volume (V_{eff}) is a sum of the proof mass and the cantilever volumes.

Table 1 shows the survey of the performance for the published piezoelectric energy harvesters.The device achieved the NPD of 1.45 $mW.g^{-2}.cm^{-3}$, being approximately 4-fold increase of that of AlN/SUS and KNN/SUS based harvesters [8-10]. For comparison, the performance of the state-of-the-art piezoelectric energy harvesters has been expressed on the NPD-frequency graph consisting of the iso-energy contours (Fig. 8). This result of this work is superior to those of the previous metallic energy harvesters and approaches closely towards the best Si-based energy harvesters.

CONCLUSIONS

This work presents the AlN/Ti-based energy harvester. AlN films were grown directly on Ti substrates with highly preferred (002) orientation. The AlN films had the FWHM of 2.3° and the normalized e_{33} of 99.92%. The micromachining process was established for fabricating the AlN/Ti-based microenergy harvesters. The output power was up to 13.1 µW at the acceleration of 10 $m.s^{-2}$. The harvester was confirmed with the high normalized power density of 1.45 $mW.g^{-2}.cm^{-3}$. This achievement was about 4-fold those of KNN/SUS- and AlN/SUS-based energy harvesters. It was comparable to those of KNN/Si- and AlN/Si-based energy harvesters. The achievement opens a door for high-performance micro energy harvesters exploiting piezo-

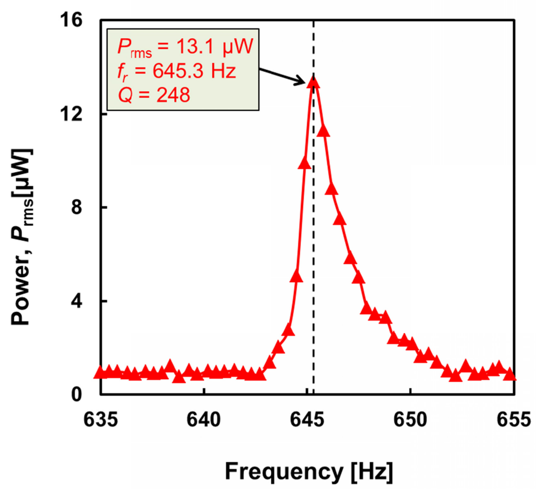

Figure 6: The power spectrum of AlN/Ti based energy harvester at 10 m/s^2 and the resistance of 1.4 MΩ.

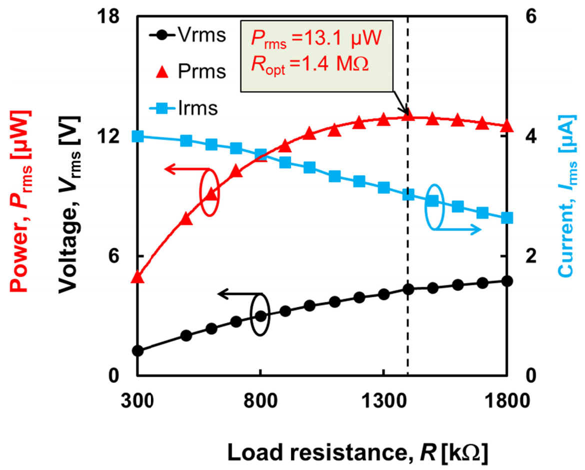

Figure 7: Output voltage, current, and power depend on the load resistance at the acceleration of 10m/s^2 and the resonant frequency of 645.3 Hz.

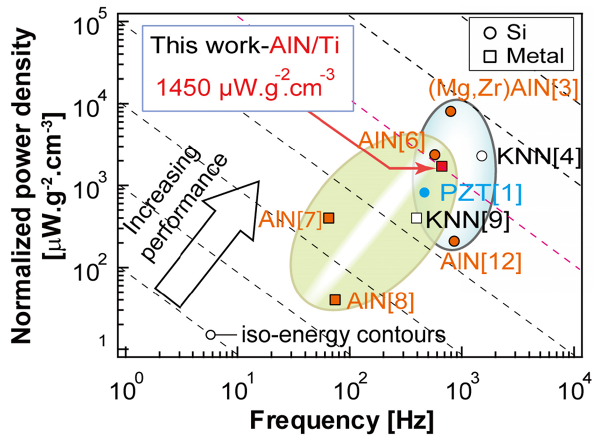

Figure 8: Power spectrum of the nonlinear harvester for different load resistances when keeping the input acceleration amplitude of 1 m/s^2

Table 1: Benchmarking of piezoelectric energy harvesters

Structure	V_{eff} [mm^3]	*a* [g]	f_r [Hz]	Power [μW]	NPD [mW.g^{-2}.cm^{-3}]
AlN/Ti (This work)	**9.01**	**1.01**	**645.3**	**13.10**	**1.45**
AlN/SUS [7]	181.95	1	64.9	72.6	0.40
AlN/SUS [8]	114.25	1	74.1	5.13	0.04
KNN/SUS [9]	NA	1	393	NA	0.40
(Mg,Zr)-AlN/Si [3]	0.245	0.8	792	1.30	8.11
AlN/Si [6]	12.73	1	30	2.36	572
KNN/Si [4]	0.31	1.01	1510	0.73	2.29
PZT/Si [5]	0.65	1	462.5	0.54	0.82

electric lead-free films on metallic Ti substrates. This leads to practical applications in which device based on Si platforms are impractical.

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