High output power AlN vibration-driven energy harvesters

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Abstract. This paper presents miniature AlN harvesters for harvesting low-frequency and two-dimensional vibration energy. A high fracture toughness and high yield strength stainless steel substrate was used to enhance output power and reduce resonate frequency of vibration energy harvesters. The thickness of 1.89 $\mu$m AlN films were deposited on 50 $\mu$m thick stainless steel (SUS) substrates for fabricating the harvesters. The Al/AlN/SUS multi-layer sheet was made into long and thin plate-like cantilevers with heavy proof masses attached at their free ends. The devices can collect vibration energy efficiently not only under perpendicular direction to the plate surface of cantilevers but also under the parallel direction. When vibration acceleration was 1.0 g, output power was 28.114 $\mu$W for perpendicular vibration and 51.735 $\mu$W for parallel vibration. When the acceleration of parallel vibration was 1.6 g, output power was 89.339 $\mu$W.

1. Introduction

To convert ambient vibration into electric energy, piezoelectric harvesters have taken great attention due to their simple configuration and high energy converting efficiency.\textsuperscript{1-3} A piezoelectric harvesters generally employ the structure of a plate-like cantilever because resonant frequency of a cantilever is much lower than that of most of other structures such as a bridge or a diaphragm, as the cantilever structure easily enables the vibration of the device to match with vibration in environment. For common piezoelectric harvesters, researchers have been thinking that they are only sensitive to vibration perpendicular to the plate surface of the cantilever due to their plate-like cantilever structures. Consequently, it is required that the plate surface of cantilevers is aligned perpendicular to the direction of the exciting vibration to realize optimal energy harvesting. However, proper alignment is sometimes prevented by the lack of knowledge about the dominant external vibration direction.

As piezoelectric harvesters are expected to be miniaturized, a challenge occurs: how to make resonant frequency of microscale or milliscale devices as low as possible? The piezoelectric element in these miniature harvesters is generally in the form of thin films that are prepared on Si substrates. High brittleness of Si (fracture toughness: about 0.9 MPa·m$^{1/2}$) incurs that a miniature harvester with the cantilever structure cannot be designed to have low resonant frequency to match the frequency of most environmental vibration sources (below 200 Hz).\textsuperscript{4-7} This is because low resonant frequency requires very thin thickness of the cantilever beam, or a heavy proof mass attached at the free end of the cantilever. However both approaches make the cantilever very vulnerable.
In this study, a lead-free AlN was employed to fabricate an energy harvester. Stainless steel (SUS 304) was used as the substrate for AlN thin films to fabricate small size piezoelectric harvesters with the plate-like cantilever structures. High fracture toughness (about 80 MPa \cdot m^{1/2}) and high yield strength (about 205 MPa) of SUS 304 enable the cantilevers to endure heavy proof masses attached at their free end to extremely reduce the resonant frequency. As shown in equation (1),

\[ f = f_0 \sqrt{0.236m/(0.236m + M)} \]  

where \( f \) and \( f_0 \) are resonant frequencies with and without a proof mass, \( m \) is the mass of a cantilever, \( M \) is mass of the proof mass. In addition, we investigate the power generating capability of the energy harvesters for the vibration perpendicular and parallel to their plate surface intending to realize two-dimensional vibration energy harvesters.

2. Fabrication of AlN vibration-driven energy harvesters

50 \( \mu \)m thick SUS304 thin sheets (length \times width: 20.0 \times 20.0 \text{ mm}) were used as substrates. AlN thin films were deposited using an electron cyclotron resonance (ECR) sputtering system in which plasma was produced by combination of static magnetic field and microwave. The details of the deposition parameters have been described in our previous report. Deposition parameters including sputtering pressure, power, gas flow rate and bias electric field applied on the substrate have been investigated to produce a high degree \( c \)-axis orientation AlN film. Table 1 shows the deposition condition of ECR sputtering. It is known that the ECR sputtering yields atoms and ions with high kinetic energy (up to 20 eV), which may lead to high residual compressive stress in thin films. In this study, 1.89 \( \mu \)m thick AlN thin films bent substrates convex upward with the bending deflection of about 4.7 mm in central of 20.0 \times 20.0 \text{ mm} AlN/SUS sheet. It is worth mentioning that intrinsic stress-induced bent structure of cantilever-based energy harvester is key point to collect two-dimensional vibration energy harvesters efficiently. A layer of 200 nm thick Al top electrode was deposited on the surface of AlN/SUS using RF magnetron sputtering. Then Al/AlN/SUS multi-layer sheet was cut into small pieces, and each piece was fixed at one end with a clamper to form a cantilever. A copper proof mass was bonded on the free end of each cantilever. Metal wires were bonded on the top electrode and SUS substrate to form a harvester. Figure 1(a) and 1(b) are the schematic illustration and the optical photograph of an obtained AlN harvester, respectively. The cantilever beam length \times width is 6.6 mm \times 9.4 mm, and the Cu proof mass length \times width \times height is 4.0 mm \times 9.4 mm \times 4.8 mm.

| Table 1. AlN film deposition condition of ECR sputtering |
|-------------------|------------------|
| Ar flow (sccm)    | 50               |
| \( \text{N}_2 \) flow (sccm) | 7.5           |
| Microwave power (W) | 500             |
| RF power (W)       | 500              |
| Substrate temperature (°C) | 280           |
| Bias voltage (V)   | 36               |

3. Characterization of AlN films

Figure 2(a) shows the X-ray diffraction pattern of AlN thin films deposited on SUS substrates. The pattern showing only (0002) peak of AlN wurtzite phase is indicating that the AlN thin films have \( c \)-axis out-of-plane orientation. The inset shows rocking curve of the AlN (0002) peak. Small full width at half maximum (FWHM) of 5.84° implies the high degree \( c \)-axis orientation of the AlN thin films suitable for fabricating high output piezoelectric harvesters. Figure 2(b) demonstrates the FE-SEM cross-sectional micrograph of the AlN/SUS structure. The micrograph indicates that columnar
grains with the diameter of tens of nanometer are grown densely along the direction perpendicular to the substrate.

Figure 1 (a) schematic illustration, and (b) optical photo of an AlN based harvester using SUS304 as substrate with a Cu proof mass.

Figure 2 (a) X-ray diffraction, and (b) FE-SEM cross-sectional micrograph of AlN thin films deposited on SUS304 substrates using ECR deposition.

4. Characterization of AlN vibration-driven energy harvesters

Vibrational output characteristics of the energy harvesters were tested using in-home setup shown in Figure 3. In this study vibration was applied along two directions: perpendicular (Figure 3b) and parallel (Figure 3c) to the plate surface of the cantilevers. For impedance matching, output power was observed for various resistive loads. Then an optimal resistive load showing maximum output power was identified to be 0.588 MΩ.

Figure 4 shows output power of the AlN based harvester as a function of vibration frequency at 0.2 g acceleration. Under perpendicular vibration condition, output power reached the maximum of 2.545 µW at resonant frequency of 66.4 Hz. Under parallel vibration condition, output power increased to 7.053 µW at the same resonant frequency. It should be noted that harvesters were more sensitive to the parallel vibration, which has been considered as improper direction for cantilever type energy harvesters. Higher output power under parallel vibration condition seemingly resulted from the bent cantilever structure and heavy proof mass used in this study. Park group also reported curled cantilever structure is important reason for efficiently harvesting parallel direction vibration. For a common piezoelectric harvester with the cantilever structure, the mass of the proof mass is usually only a few times that of the cantilever beam. However, in this study the mass of the proof mass is about 170 times that of the cantilever beam.
Figure 3 Schematic of (a) vibrational output characteristics measurement set up and energy harvester mount configuration of (b) vibration in perpendicular direction and (c) vibration in parallel direction.

Figure 4 Output power vs. vibration frequency of an AlN harvester under perpendicular and parallel vibration at 0.2 g acceleration.

Figure 5 displays output power as a function of vibration acceleration. Under both perpendicular and parallel vibration conditions, output power increased at an exponential rate with the increase of acceleration. When the acceleration was increased to 1.0 g, the power was 28.114 µW for perpendicular vibration and 51.735 µW for the parallel vibration. When the acceleration of the parallel vibration was 1.6 g, the power was 89.339 µW, which exceeds the record of 85 µW for AlN/Si harvesters with the comparable size. As shown in Figure 5, at low acceleration level (0.1~0.7 g), the slope of the double logarithmic plot for “perpendicular driven-vibration case” is equal to 1.68 (line $l_1$), indicating the output power increases almost quadratically with acceleration. At higher acceleration levels (0.8~1.0 g), the slope of line $l_2$ seems to reduce toward a value of 1, may be due to increased air damping at violent vibration and smaller piezoelectric constant under larger stress. However, the slope of line $l_3$ was 1.17 for “parallel driven-vibration case”, indicating stronger damping occurred in this type driven-vibration whether it is in the low or high acceleration levels. The output power of 85 µW in ref. 10 is a result measured in vacuum. This literature also showed that output power in air dramatically decreased by almost one order of magnitude due to air damping. Therefore, we plan to package our devices in vacuum to eliminate air damping and enhance output power in the future work.
5. Conclusions

In summary, the energy harvesting of low-frequency and two-dimensional vibration was realized in millimeter-scale AlN based harvesters with the cantilever structure. The SUS substrate ensured that a cantilever can endure a heavy proof mass at its free end to extremely reduce the resonant frequency. Moreover, the heavy proof mass and bent cantilever structure made the device sensitive to two-dimensional vibration: the perpendicular and parallel to the plate surface of the cantilever. When vibration acceleration was 1.0 g, output power was 28.114 µW for perpendicular vibration and 51.735 µW for parallel vibration. When the acceleration was 1.6 g, output power was 89.339 µW for parallel vibration. The results in this study will give valuable information to develop high output power vibrational energy harvesters.

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