HIGH OUTPUT-POWER MICROGENERATOR USING MgHfAl-N FILM

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ABSTRACT

This talk presents the piezoelectric thin film manufactured by a magnetron sputtering system. In the system Mg and Hf are co-doped into the Al site of AlN, the apparatus including: a target made of AlN; a plurality of first pieces made of Mg arranged on a surface of the target; and a plurality of second pieces made of Hf arranged on the surface of the target

In the piezoelectric thin film manufacturing apparatus and the piezoelectric thin film manufacturing method, it is possible to easily control the doping ratio of Mg and Hf by controlling the ratio of the average surface area. In particular, by controlling the average surface area of each of the first pieces to be 0.9 to 1.1 times the average surface area of each of the second pieces, a piezoelectric thin film of $(MgHf)_xAl_{1-x}N$ deposited on stainless steel foil substrate having an excellent FoM and piezoelectric strain constant can be obtained.

Finally, we manufactured a micro-generator with the maximum output-power of 36mW.

KEYWORDS

Piezoelectric thin films, MgHf co-doped AlN, high-throughput development, microgenerators, vibration energy harvesters.

INTRODUCTION

In recent times, there has been a remarkable surge in the development of micro-generators as the power sources for wireless sensor networks (WSNs)[1,2]. As the number of elements within these networks continues to increase significantly, there is a growing demand for miniaturized and high-performance generators. This has initiated a competition to adopt exceptionally efficient materials.

Currently, lead zirconate titanate (PZT) stands as the predominant choice for piezoelectric applications in sensors and actuators [3, 4]. PZT, however, is not the ideal material for power generation in microgenerator due to its high relative dielectric constant (ε_r of 1118 [4]). Also, lead, one of the principal components of PZT, has encountered industrial usage restrictions.

Among the potential alternatives to PZT, Aluminum nitride (AlN) films have been drawing significant attention for their inherent piezoelectric properties, which enable the conversion of mechanical vibrations into electricity [4]. However, the piezoelectric response of pure AlN films is limited, necessitating the introduction of dopants to enhance its performance. Numerous endeavors have been undertaken, including the incorporation of single dopants such as Sc [5], Ta [6], and Yb [7], as well as co-dopants like MgZr [8], MgTi [9], and ZnTi [10]. From the viewpoints of cost-effectiveness and industrial applicability, we presented the novel concept involving practical films composed of $(MgHf)_xAl_{1-x}N$, which holds tremendous promise for advanced sensors and microgenerators [11, 12].

In previous studies, our focus was exclusively on films doped at a concentration of 10 at% [11, 12], resulting in a lack of understanding regarding the properties of highly doped films. The output power of the $(MgHf)_{0.1}Al_{0.9}N$-based device were increased with the MgHf-dopants concentration. The obtained power at $x = 0.1$ was 5-times that of the pure AlN. This harvester provided an *NPD* of 34.9 $mW.g^{-2}.cm^{-3}$, being approximately 18-time higher than that of the published AlN-based VEHs.

In this paper, a piezoelectric thin film of $(MgHf)_xAl_{1-x}N$ deposited on stainless steel foil substrate having an excellent FoM with 65GPa and piezoelectric strain constant with d_{31}=9.8pm/V can be obtained. Finally, we manufactured a miniature size micro-generator with the maximum output-power 36mW for a practical use.

EXPERIMENTAL PROCEDURES

$(Mg,Hf)_xAl_{1-x}N$ ($x = 0 \sim 0.44$) films were developed by a reactive magnetron sputtering with Mg-Hf and AlN targets in Ar/N_2 ambient. The details are shown in the table 1.

Table 1: The sputtering conditions of MgHfAl-N films

AMS	**System**	Magnetron AC sputtering
	Target	*Mg + Hf + Al*
	Gasses	*$Ar + N_2$*
	Gas flow	*10 sccm:60 sccm*
	Base pressure	2×10^{-6} *Torr*
	AC power	5 kW
	Deposition rate	40 nm/min

Prior to each deposition, the sputtering chamber was evacuated to base pressure below 1×10^{-7} Torr, the targets have been pre-sputtered for 20 minutes in argon (Ar) and subsequently for 10 minutes in a mixture of Ar and nitrogen (N_2). The RF power applied to the AlN and MgHf targets was 140 W and 100 W, respectively. Throughout the deposition process, the $Ar:N_2$ flow rate was maintained at 8:32 sccm.

Crystallinity of the $(MgHf)_xAl_{1-x}N$ thin film was investigated using an X-ray diffractometer (Brucker-D8 advance) with θ-2θ scans, employing a focused X-ray beam with a spot size of approximately 1.0-mm in diameter.

The piezoelectric thin film manufactured by the magnetron sputtering system. In the system Mg and Hf are co-doped into the Al site of AlN, the apparatus including: a target made of AlN; a plurality of first pieces made of Mg arranged on a surface of the target; and a plurality of second pieces made of Hf arranged on the surface of the target, wherein an average surface area of each of the plurality of first pieces is 0.9 to 1.1 times an average surface area of each of the plurality of second pieces with respect to a surface area of the target

RESULTS AND DISCUSSIONS

A typical XRD pattern of MgHfAl-N deposited on stainless steel foil substrate is shown in Figure 1. Peaks of MgHfAl-N, Pt and SUS430 are obserabed.

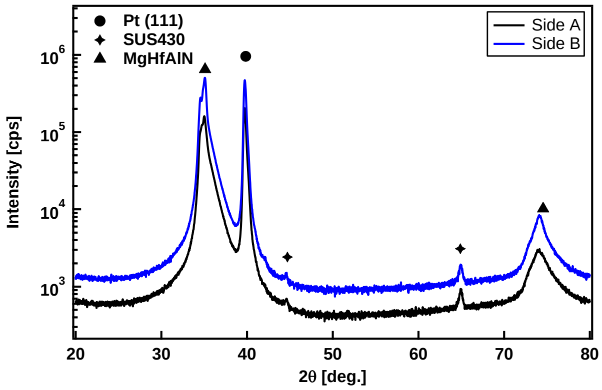


Figure 1: A typical XRD pattern of MgHfAl-N thin film deposited on Pt/stainless steel foil substrate.

The d_{33} (piezoelectric strain constant) was determined for various values of x for the manufactured $(MgHf)_xAl_{1-x}N$ thin film deposited on cantilver. A sinusoidal voltage was applied between the piezoelectric thin film and the cantilever, and the displacement between the surface of the piezoelectric thin film and the tip of the cantilever was measured using a laser Doppler vibrometer (LV-1710 manufactured by Ono Sokki Co., Ltd.). The cantilever used had a Pt-coated surface. The applied voltage was set to 0 to ±20 V_{pp}, and the frequency was set to 1 to 10 kHz.

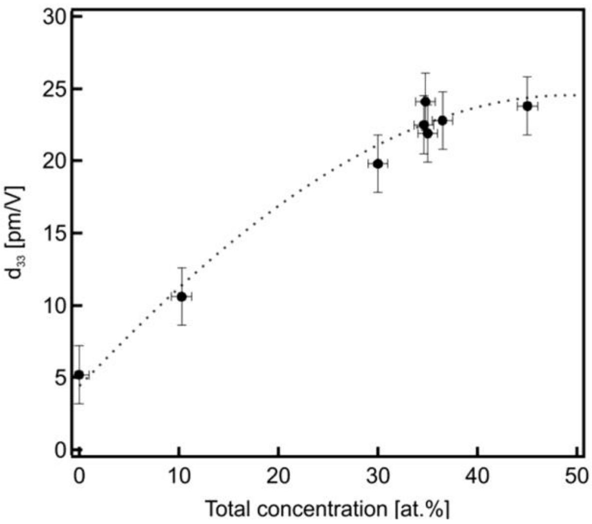


Figure 2: The d_{33} (piezoelectric strain constant) for various values of x for the manufactured $(MgHf)_xAl_{1-x}N$ thin film.

The values of d_{33} for various values of x are shown in Fig. 2. The horizontal axis of Fig. 2 is the total concentration of MgHf, where the value of x is expressed in atomic percentage (at.%). As shown in Fig. 2, it was confirmed that the value of d_{33}.

Next, the relative dielectric constant (ε_γ) and piezoelectric strain constant d_{31} of the $(MgHf)_xAl_{1-x}N$ thin film were measured at various values of x to obtain the figure of merit (FoM). First, a $(MgHf)_xAl_{1-x}N$ thin film was formed on a cantilever-shaped substrate. The Pt/Ti of the substrate was used as the lower electrode, and an Au/Cr layer serving as the upper electrode was formed on the surface of the $(MgHf)_xAl_{1-x}N$ thin film. In this way, $(MgHf)_xAl_{1-x}N$ thin films with various values of x were formed to manufacture measurement samples. The cantilever part of the measurement sample had a width of 1000 μm, the $(MgHf)_xAl_{1-x}N$ thin film had a thickness of 5 μm, and the substrate had a thickness of 50 μm.

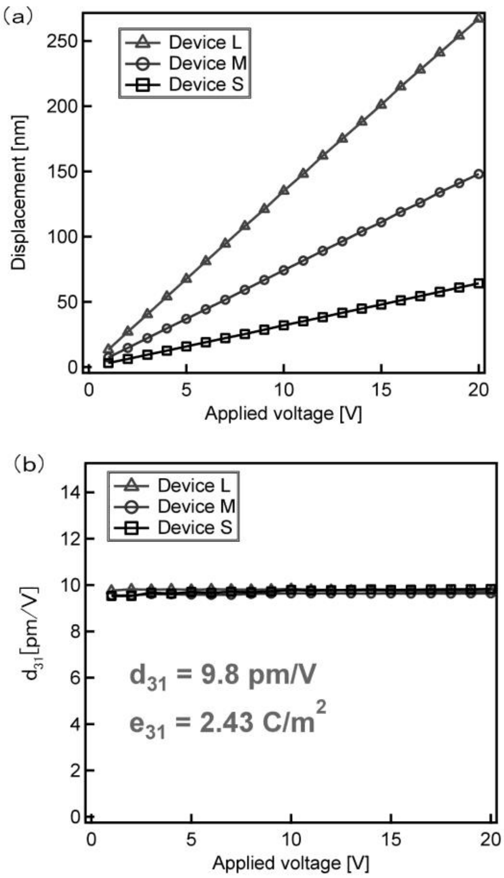


Figure 3: The relative dielectric constant (ε_γ) and piezoelectric strain constant d_{31} for the $(MgHf)_xAl_{1-x}N$ thin film

In addition, to avoid geometric errors, measurement samples having cantilever beams with three different lengths, 2000 μm (Device S), 3000 μm (Device M), and 4000 μm (Device L), were manufactured.

For various values of x, the cantilevers of three types of measurement samples were vibrated to determine their respective resonant frequencies, and the Young's moduli were calculated from the amount of deviation of each resonant frequency, and the average value was calculated. A vibration control device (G-Master APD-200 FCG manufactured by Asahi Manufacturing Co., Ltd.) was used to vibrate the cantilever, and a laser Doppler vibrometer (LV-1710 manufactured by Ono Sokki Co., Ltd.) was used to measure the vibration of the cantilever. As a result, for example, when x=0.45 for the $(MgHf)_xAl_{1-x}N$ thin film, the resonant frequencies of the measurement samples of Devices S, M, and L were 13884 Hz, 6148 Hz, and 3487 Hz, respectively, and the Young's moduli were 253 GPa, 245 GPa, and 249 GPa, respectively. The average value of the Young's moduli was 249±10 GPa.

Next, a static voltage of 0 to ±20 V_{pp} was applied between the lower and upper electrodes of each measurement sample, and the displacement of the tip of the cantilever was measured. Fig. 3(a) shows the relationship between the applied voltage and the displacement obtained for the measurement samples of Devices S, M, and L when x=0.2. Fig. 3(b) shows the relationship between the applied voltage and the piezoelectric strain constant d_{31} calculated from the displacement in Fig. 3(a). As shown in Fig. 3(b), it was confirmed that the value of d_{31} was constant at approximately 9.8 pm/V regardless of the applied voltage. The piezoelectric stress constant e_{31} was calculated as the product of d_{31} and Young's modulus, and was approximately 2.43 C/m^2.

Next, a voltage of 0 to ±20 V_{pp} at 10 kHz was applied between the lower and upper electrodes of each measurement sample, and the capacitance of the $(MgHf)_xAl_{1-x}N$ thin film was measured to determine the relative dielectric constant (ε_γ). Fig. 4 shows the relationship between the frequency and capacitance obtained for the measurement sample of Device M when x=0.2. The relative dielectric constant (ε_γ) was calculated as 16±0.4 from the results in Fig. 4. From this relative dielectric constant (ε_γ) and the piezoelectric stress constant e_{31} calculated in Fig. 3, the FoM at this time was calculated as 41.7±1.0 GPa.

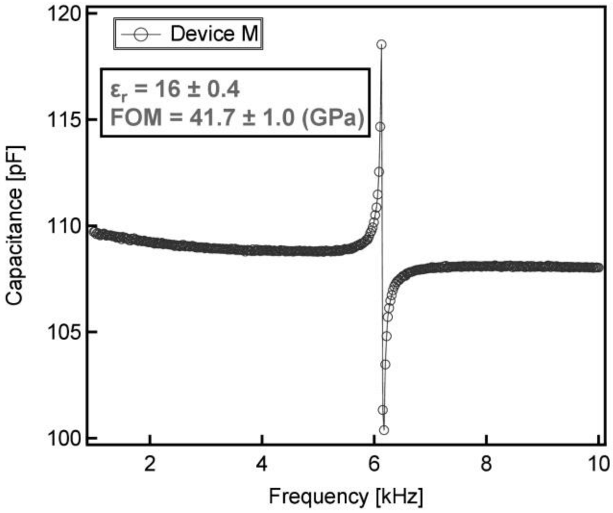


Figure 4: Capacitance for each frequencies at x=0.2.

The relationship between various values of x and FoM calculated in a similar manner is shown in Fig. 5. The horizontal axis of Fig. 5 is the total concentration of MgHf, where the value of x is expressed in atomic percentage (at.%). As shown in Fig. 5, it was confirmed that the value of FoM increases with increasing x, and is about 45 GPa or more when x=0.3 (30 at.%), about 65 GPa or more when x=0.44 (44 at.%), and the value is saturated around x=0.5.

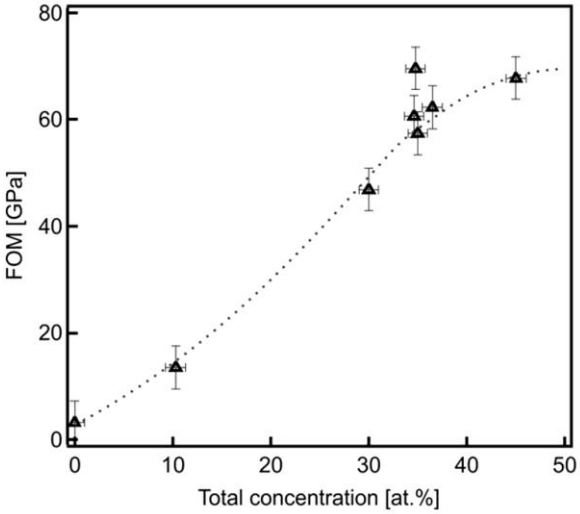
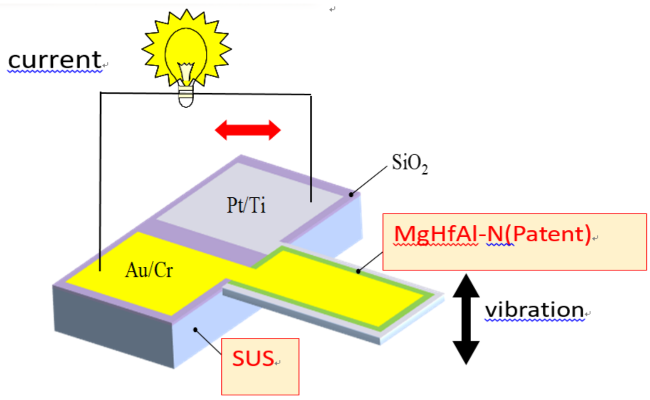
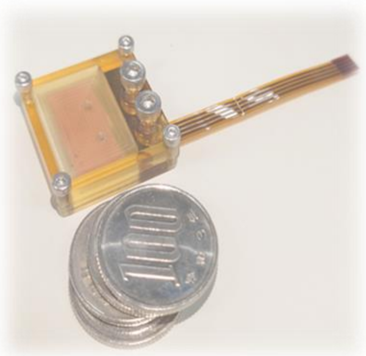


Figure 5: The relationship between various values of total concentration x and FoM.

Finally, trial micro-generator was manufactured as shown in Figure 6. The device principle is shown in Figure 6(a) and it’s photograph in (b). The MgHfAl-N film is deposited on the face and backside of the cantilever.



(a)



(b)

Figure 6: The trial micro-generator using MgHfAl-N thin film. (a) The structure principal. (b) A photograph of the trial device.

The device was packaged by a engineering plastic material. The outside dimension of the package is 26 x 26 x 6 mm^3.

Figure 7 shows the output power spectra of the trial micro-generator using $(MgHf)_xAl_{1-x}N$ thin film (x=0.44) at 1G. The piezoelectric MgHfAl-N film is deposited on both side of surface and backside of the stainless steel foil cantilever. The maximum output power with 36.2mW is realized.

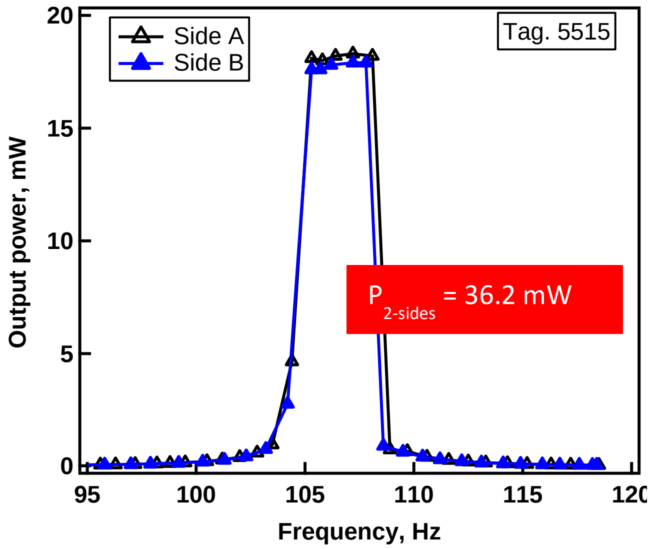


Figure 7: The output power spectra of the trial micro-generator at 1G. The maximum output power shows 36.2mW in the range of 104.2-108.1Hz. Bandwidth is 3.9Hz.

CONCLUSIONS

$(MgHf)_xAl_{1-x}N$ films were grown on Pt/stainless steel foil substrates. The microstructure and electrical properties had been measured. The trial micro-generator was manufactured The film has high FoM with 65 GPa and maximum output ower with 36.2 mW was realized. The results are promising for further enhancement since the geometric optimization.

ACKNOWLEDGEMENTS

The authors would like to thank Profs. Oguchi and Hane for their valuable suggestions and comments. The authors are grateful to Micro /NanoMachining and Education Center (MNC), and the Hands-on-access fabrication facility at the Nishizawa Research Center, Tohoku University, for their valuable support during experiments. This work is financially support by the OPERA project of the Japan Science and Technology Agency and the SAPO-IN project of The small and Medium Enterprise Agency. METI. Also, This work was supported by JSPS KAKENHI Grant Number JP20K15146.

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