MgHf CO-DOPED AlN THIN FILMS TOWARD LOW SIGNAL-TO-NOISE RATIO IN PIEZOELECTRIC MICROMACHINED ULTRASONIC TRANSDUCERS

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ABSTRACT

This paper introduces innovative MgHf co-doped aluminum nitride ($(\mathrm{MgHf})_x\mathrm{Al}_{1-x}\mathrm{N}$) based piezoelectric micromachined ultrasonic transducers (PMUTs), showcasing an impressive signal-to-noise ratio (SNR). Through the development of high-quality $(\mathrm{MgHf})_x\mathrm{Al}_{1-x}\mathrm{N}$ films, we successfully achieved a high piezoelectric coefficient (d_{31}) of 11.9 pC/N, which is nearly six times increased compared to that of pure AlN (2.3 pC/N). Consequently, the SNR reached 54.86 ($\times 10^5$ $\mathrm{Pa}^{0.5}$) at $x = 0.4$, representing a threefold increase compared to pure AlN (~ 19.89×10^5 $\mathrm{Pa}^{0.5}$) and 1.5-times higher than the previously reported highest value achieved with Sc-doped AlN. By tailoring the $(\mathrm{MgHf})_x\mathrm{Al}_{1-x}\mathrm{N}$ films, we successfully fabricated the first prototype $(\mathrm{MgHf})_x\mathrm{Al}_{1-x}\mathrm{N}$-based PMUT array. The performance evaluation of the PMUTs is also presented in this report.

KEYWORDS

MgHf co-doped AlN thin film; piezoelectric micromachined ultrasonic transducers (PMUTs); Ultrasonic sensor, time-of-flight sensors

INTRODUCTION

Recently, there has been a significant surge in the development of Piezoelectric micromachined ultrasonic transducers (PMUTs) for various applications, including medical imaging, non-destructive testing, and proximity sensing, owing to their small size and ability to convert electrical signals into mechanical vibrations and vice versa [1, 2]. However, achieving a high signal-to-noise ratio (SNR), essential for improving the accuracy and reliability of these devices, remains a persistent challenge in PMUT technology. These highly efficient and miniaturized devices necessitate the adoption of novel materials with enhanced properties.

Aluminum nitride (AlN) films have garnered considerable interest due to their inherent piezoelectric properties, which facilitate their use in PMUTs. However, the intrinsic noise and constrained piezoelectric response of pure AlN films [3] can limit the SNR in PMUTs, thereby restricting their performance in high-precision applications. To address these issues, doping AlN with suitable elements has been explored as a strategy to enhance its piezoelectric properties while maintaining favorable dielectric characteristics, such as a low dielectric loss (<0.1%). Recently, Q. Wang et al. introduced ScAlN as a promising candidate for flexural PMUT devices utilizing the transverse piezoelectric mode [4]. Additionally, T. Higuchi et al. [5] achieved a highly doped Sc-AlN thin film with a dielectric loss of 0.07%, a 30% improvement compared to pure AlN, by employing thermal post-treatment.

From the perspective of cost-effectiveness and industrial applicability, we introduced MgHf co-doped AlN films, $(\mathrm{MgHf})_x\mathrm{Al}_{1-x}\mathrm{N}$, as an alternative for use in PMUTs. Co-doping significantly enhanced the piezoelectric properties of AlN [6, 7]. In this study, we further advanced dielectric and piezoelectric properties of $(\mathrm{MgHf})_x\mathrm{Al}_{1-x}\mathrm{N}$ thin films by optimizing crystal quality and reducing defect density in the films.

Focusing on the development and characterization of MgHf co-doped AlN thin films, we aimed at improving the SNR in PMUTs. By systematically investigating the effects of MgHf co-doping on the structural, electrical, and piezoelectric properties of AlN, we sought to establish a foundation for enhancing the performance of PMUTs in demanding applications. The findings of this research could pave the way for more efficient and reliable PMUT designs, thereby expanding their applicability in high-precision fields.

EXPERIMENTAL PROCEDURES

The 5-µm-thick $(\mathrm{MgHf})_x\mathrm{Al}_{1-x}\mathrm{N}$ film was deposited on $\mathrm{Pt/Ti/SiO_2/Si}$ substrates using reactive AC sputtering (AMS212-1-S) with Mg-Hf integrated Al-target in Ar : $\mathrm{N_2}$ ambient (Figure 1). By adjusting the number of Mg and Hf pieces, we successfully obtained films with high crystallinity and a composition range of $0 < x < 0.5$. The Ar-to-$\mathrm{N_2}$ gas ratio was carefully controlled to fine-tune the residual stress in the thin film. A high sputtering-rate of ~1.7 nm/s was obtained by using this method. Sputtering conditions were detailed and discussed in earlier study [8].

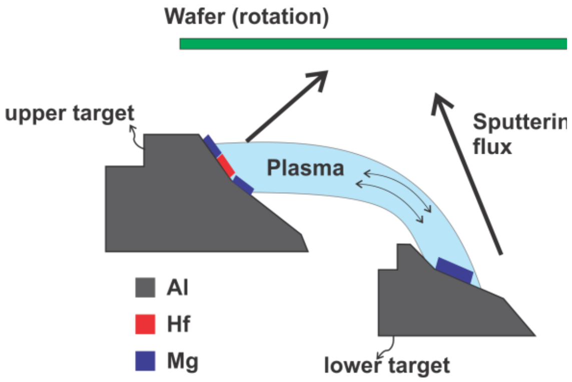

Figure 1: AC reactive sputtering illustration for the deposition of MgHf co-doped AlN

The crystallinity of the as-deposited films were examined by an 2D-Xray-diffractometer (Brucker D8-advanced). Elemental composition across the wafer was determined using an EDX detector integrated into a field-emission scanning electron microscope (FE-SEM, Hitachi SU-70 FESEM) was utilized to determine the elemental composition throughout the wafer.

To showcase the outstanding piezoelectric characteristics of $(MgHf)_xAl_{1-x}N$ thin films, we fabricated micro cantilevers composed of $(MgHf)_xAl_{1-x}N/Si$ [6] These cantilevers served as a valuable tool for assessing the piezoelectric properties of the thin film. Young's modulus (Y) and the piezoelectric coefficients (d_{31}/e_{31}) of the developed films were measured using the resonant method and steady voltage-induced displacement of the micro cantilevers, respectively [9]. The sequential measurement procedures were discussed in [7].

Dielectric properties of $(MgHf)_xAl_{1-x}N$ thin film with various concentration was calculated by measuring the capacitance of a planar capacitor using an impedance analyzer (HP4194A) [6]. The planar capacitors consisted of a Pt bottom electrode, a $(MgHf)_xAl_{1-x}N$ film, and an Au top electrode (ϕ = 0.1 mm) Through this measurement, dielectric loss of thin films was also determined.

RESULTS AND DISCUSSIONS

Materials properties

Piezoelectric coefficient (d_{31}) of $(Mg,Hf)_xAl_{1-x}N$ thin film was shown in fig. 2. As a result of doping, the d_{31} increases significantly with rising dopant concentration. The thin film demonstrated its highest piezoelectric coefficient of 11.9 pC/N was achieved at $x = 0.45$. However, when the concentration increased to $x = 0.48$, the d_{31} value significantly decreased, consistent with theoretical predictions by Qiaoya L. V. et al. [10]. The $(Mg,Hf)_xAl_{1-x}N$ thin film exhibited superior piezoelectric properties compared to our previous report [11], as the deposition conditions were carefully optimized to produce films with higher crystallinity, greater density, and fewer defects.

From the planar capacitor measurements, the relative permittivity (ε_r) showed a continuous increase from 10.3 to 14.2 with the increasing of dopant concentration. The dielectric loss of the thin films remained stable during the doping process, with values of approximately 0.3% (on Si substrates) and 0.5% (on SUS substrates).

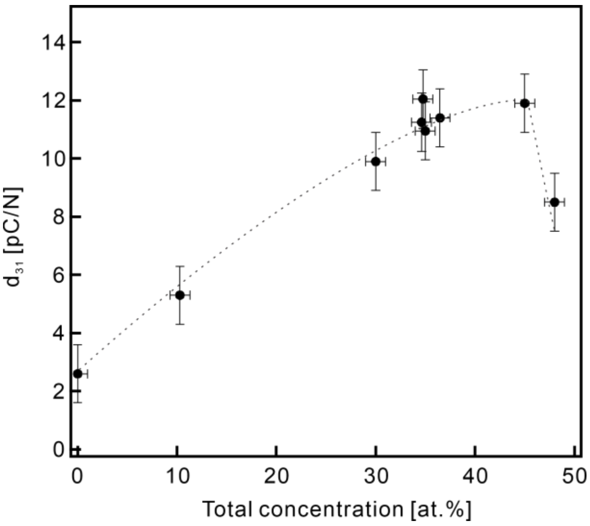

Figure 2: Dependence of piezoelectric coefficient (d_{31}) of $(MgHf)_xAl_{1-x}N$ on doping concentration ($0 < x < 0.5$)

The Young's modulus (Y) of thin film was calculated by measuring the change in the resonant frequency ($\Delta\omega$) of the micro cantilevers before and after deposition of the $(Mg,Hf)_xAl_{1-x}N$ films [12]. The obtained value of Y exhibited a continuous decrease, reaching 283 GPa on Si substrate and 249 GPa on SUS430 substrate as the dopants concentration increased. The changes in dielectric properties and Young's modulus of the thin films were previously analyzed and discussed in detail in our earlier report [6].

To enable comparison with various piezoelectric materials, a survey of published materials suitable for PMUTS is summarized in Table 2. The signal-to-noise ratio (SNR, $e_{31}/(\varepsilon_r \times \varepsilon_0 \times \tan\delta)^{1/2}$) accomplished by our thin film was found to be 54.86 $\times 10^5$ $Pa^{0.5}$, which is more than three times higher than that of pure AlN thin films on Si substrates (~19.89×10^5 $Pa^{0.5}$) and 1.5 times greater than the previously reported highest value obtained with Sc-doped AlN (~36.84×10^5 $Pa^{0.5}$). Furthermore, our $(Mg,Hf)_xAl_{1-x}N$ thin film grown on polished SUS430 demonstrated an impressive SNR of of 35.66 $\times 10^5$ $Pa^{0.5}$, comparable to the values reported for Sc-AlN films.

Table 1. benchmarking of 40 at. % MgHf doped AlN, $(MgHf)_{0.4}Al_{0.6}N$

Material	**Substrate**	**Dielectric constant**	**Piezoelectric coefficient**		**Young's Modulus**	**Dielectric loss @ *10 kHz***	**Signal-to-noise ratio**
		ε_r	e_{31}, C/m^2	d_{31}, pC/N	Y, GPa	$\tan\delta$	$\times 10^5$ Pa$^{0.5}$
MgHf-AlN	*Si*	*14.3*	*3.38*	*11.9*	*283*	*0.003*	*54.86*
	SUS430	*15.6*	*3.0*	*11.9*	*249*	*0.005*	*35.66*
AlN [3]	Si	10.5	1.05	2.7	395	0.003	19.89
ZnO [3]	Si	10.9	1	4.8	208	0.05	4.55
PZT [15]	Si	800	10	102.0	98	0.02	8.40
SC-PZT [16]*	Si	308	24	244.9	98	0.02	32.50
PMNPT [17]	Si	250	14.5	148.0	98	0.015	25.17
Epi. PZT [18]	Si	500	10.5	138.2	76	0.02	11.16
Sc-AlN [4, 14]	Si	16	3.1	13.7	227	0.005	36.84

*Estimated from the references

PMUTs prototype and performance

To demonstrate the high potential of our (Mg,Hf)$_x$Al$_{1-x}$N films for PMUTs application, we developed arrays of diaphragm resonant type PMUTs by micromachining techniques. Each PMUTs element consists of a 5-µm (Mg,Hf)$_x$Al$_{1-x}$N films sandwiched between top (Au/Cr) and bottom (Pt/Ti) electrodes. The (Mg,Hf)$_x$Al$_{1-x}$N diaphragm serves as the vibrating component and represents the most critical part of the PMUT. Notably, this diaphragm is formed solely from the piezoelectric (Mg,Hf)$_x$Al$_{1-x}$N thin film without any supporting Si layer. This structure enables the device to generate a high output signal.

Fabrication process of the PMUTs arrays involved etching the (Mg,Hf)$_x$Al$_{1-x}$N using a high density Cl-based plasma, followed by etching the Si layer using the Bosch process, as described in our previous reports[6, 13]. Precise control over the Si etching process is crucial to achieving a thin, high-quality (Mg,Hf)$_x$Al$_{1-x}$N diaphragm.

Figure 3 illustrates an PMUT element comprising a 5-µm-thick (MgHf)$_x$Al$_{1-x}$N film sandwiched between top and bottom electrodes, serving as the vibrating component. An array of PMUTs was successfully fabricated by micromachining processes, as shown in fig. 4. A total of 128 PMUTs were constructed within a 4 × 4 mm² device area to further enhance the output signal.

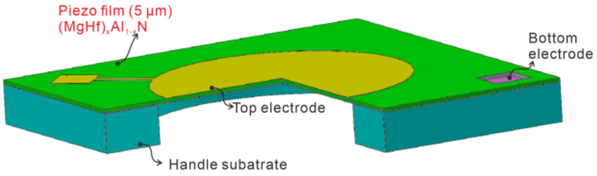

Figure 3: Illustration of a Piezoelectric micromachined ultrasonic transducers tailoring 5 µm (MgHf)$_x$Al$_{1-x}$N film

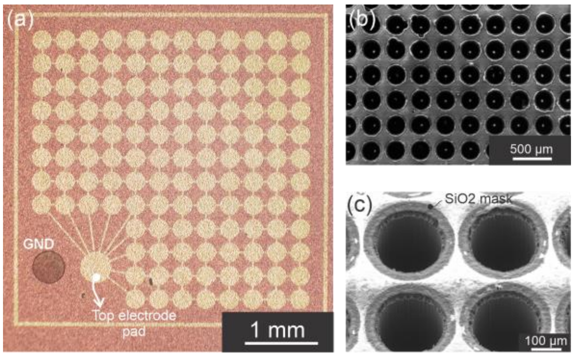

Figure 4: Optical microscope ((a) top view) and SEM ((b) and (c)bottom view) images of PMUTs array with diaphragm diameter of 200 µm and piezo thickness of 5 µm

The performance of these devices was initially evaluated using an impedance analyzer (HP4194A), as depicted in fig. 5. The PMUTs demonstrated resonant and anti-resonant frequency at 237 kHz and 252 kHz, respectively. By utilizing high-quality (MgHf)$_x$Al$_{1-x}$N film, we achieved an impressive d_{31} value without an increase in the loss tangent (tanδ) compared to pure AlN (~0.3%). This resulted in a significant improvement in the SNR $(e_{31}/(\varepsilon r\times\varepsilon 0\times\tan\delta)^{1/2})$ [1, 3, 14], reaching 54.86 ×10^5 Pa$^{0.5}$, which is three times higher than that of pure AlN (~ 19.89×10^5 Pa$^{0.5}$) and 1.5-times greater than the highest value achieved by Sc-doped AlN [6].

The performance of (MgHf)$_x$Al$_{1-x}$N-based PMUTs as ultrasonic transmitter and receiver was shown in Figure 6. Two PMUTs were positioned approximately 10 mm apart. Five 252-kHz pulses were applied to the transmitter, and the signal received by the receiver was recorded. The results indicate a time-of-flight of 28.1 µs.

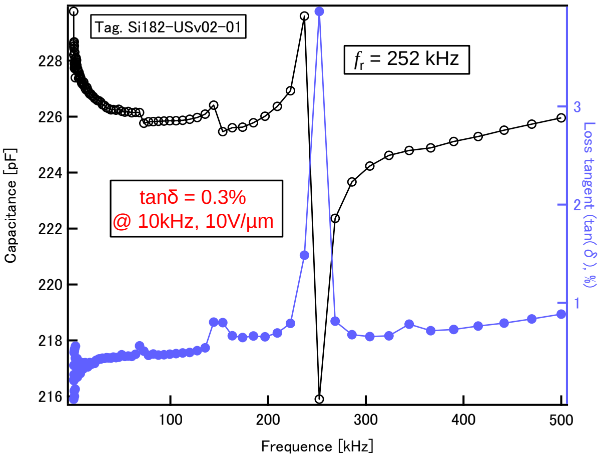

Figure 5: Capacitance measurement of the device with 5-µm (Mg,Hf)$_x$Al$_{1-x}$N diapgragm

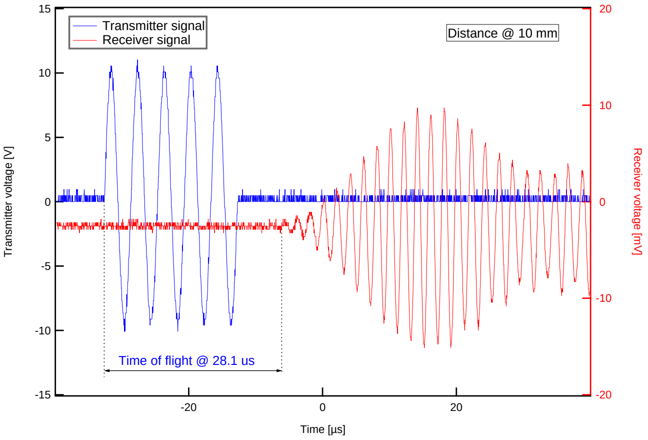

Figure 6: Fabricated PMUTs work as ultrasonic transmitter and receiver at the distance of 10 mm. Time of flight was determined at 28.1 us.

CONCLUSIONS

In this study, we demonstrated the significant potential of (Mg,Hf)$_x$Al$_{1-x}$N thin films for piezoelectric micromachined ultrasonic transducers (PMUTs). By optimizing the deposition process, crystal quality, and doping concentration, we achieved exceptional piezoelectric and dielectric properties, including a d_{31} value of 11.9 pC/N and a signal-to-noise ratio (SNR) of 54.86 ×10^5 Pa$^{0.5}$. These values represent a threefold improvement in SNR compared to pure AlN and are 1.5 times higher than the highest value reported for Sc-doped AlN films.

The PMUT arrays, which utilized $(Mg,Hf)_xAl_{1-x}N$ diaphragms without a supporting Si layer, were successfully fabricated and subjected to initial performance evaluation. Ultrasonic transmission and reception experiments validated the practical functionality of the devices, with a time-of-flight measurement recorded at 28.1 µs for an approximate transmission distance of 10 mm.

These findings highlight the advantages of $(Mg,Hf)_xAl_{1-x}N$ as a cost-effective, high-performance alternative to the conventional piezoelectric materials, paving the way for PMUTs in advanced and precise applications. Future work will focus on further optimizing device design and exploring new applications for these high-performance PMUTs.

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