

Article

Development of Piezoelectric Thin-Film Ultrasonic Transducers for Wind Turbine Bolt Preload Measurement

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Abstract

The detection of bolt preload force is of vital importance for ensuring the structural reliability of equipment under extreme operating conditions. Traditional ultrasonic transducers based on bulk piezoelectric materials suffer from poor long-term coupling stability and high brittleness of the material, which limits their practical applications. In this work, AlN piezoelectric thin films were fabricated by RF magnetron sputtering, and the effects of RF power and target-to-substrate distance on film morphology, crystal structure, and ultrasonic response were investigated. The results show that increasing RF power increased the film thickness and deposition rate, reduced the detected O content on the film surface, and changed the XRD response. The film deposited at 900 W generated ultrasonic longitudinal wave echoes with a relatively high signal amplitude among the tested RF powers. Among the tested target-to-substrate distances, the film deposited at 60 mm showed a relatively higher deposition rate and generated an ultrasonic longitudinal wave echo with a relatively higher amplitude. The measured d_{33} value of this film was approximately 4.8 pC/N. The AlN thin-film ultrasonic transducers prepared under the selected deposition conditions were directly deposited on bolts, and the effects of temperature and axial load were calibrated using the ultrasonic TOF measurement method. There was a linear correlation between the TOF and the temperature ($R^2 > 99.99\%$), as well as between the TOF and the axial load. These results indicate that the deposited AlN thin-film transducer has potential for bolt preload measurement in wind turbine bolts.

Keywords: AlN thin film; RF powers; target-to-substrate distances; ultrasonic longitudinal wave; bolt preload



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1. Introduction

Wind power generation relies on high-strength bolted connections to maintain the structural integrity of wind power units under complex mechanical loads and dynamic environmental conditions. The preload of these bolts directly influences vibration stability, fatigue life, and overall operational safety. Insufficient or uneven preload can lead to bolt loosening, stress concentration, and potential failure of critical structural components, posing significant risks to the reliability and maintenance of wind power systems [1,2]. Therefore, accurate and real-time monitoring of bolt preload is essential for ensuring the

safe and stable operation of wind power units [3]. Conventional techniques, including torque-based methods, strain gauges, and optical fiber sensors, often suffer from indirect measurement, limited durability, or complex installation requirements, restricting their widespread adoption in practical wind power applications [4,5]. Ultrasonic time-of-flight (TOF) methods have emerged as a promising alternative due to their non-destructive nature, high sensitivity, and capability for in situ monitoring of bolt preload [6,7].

Piezoelectric materials are key to ultrasonic transducers. Lead zirconate titanate (PZT) is widely used for its high piezoelectric coefficient and strong electromechanical coupling. However, PZT is brittle, prone to mechanical failure under high stress, and often incompatible with direct integration onto metallic bolts, which limits its practical use for wind power bolt monitoring [8,9]. Zinc oxide (ZnO) thin films offer good piezoelectric response and process compatibility, yet their mechanical strength and acoustic velocity are lower than those of metallic substrates, reducing their efficiency in high-load, high-frequency bolt applications [10]. Aluminum nitride (AlN) thin films, in contrast, provide a unique combination of properties ideal for wind power bolts. AlN exhibits high mechanical strength, excellent acoustic longitudinal wave velocity, and chemical inertness, ensuring robust ultrasonic signal generation and propagation under mechanical stress [11,12]. Furthermore, AlN is compatible with thin-film deposition processes and metallic substrates, enabling direct deposition on bolts without additional coupling agents. Although the intrinsic piezoelectric coefficient of AlN is lower than that of PZT or ZnO, its mechanical robustness, acoustic properties, and integration capability make it a candidate material for bolt preload sensing in wind power units [13].

The properties of AlN thin films are affected by deposition conditions during radio frequency (RF) magnetron sputtering [14,15]. Parameters such as RF power and target-to-substrate distance can influence the transport behavior of sputtered species, thereby affecting film morphology, elemental composition, thickness, and crystallographic texture. These film characteristics may further influence the piezoelectric and ultrasonic responses of AlN thin-film transducers [16]. In this work, AlN piezoelectric thin films were fabricated by RF magnetron sputtering, and the effects of RF power and target-to-substrate distance on film morphology, composition, crystal structure, piezoelectric response, and ultrasonic response were investigated. Based on the selected deposition conditions, AlN thin-film transducers were directly deposited onto wind power bolts, and their preload measurement response was evaluated using the ultrasonic TOF method. This study explores the potential of directly deposited AlN thin-film transducers for bolt preload measurement in wind power applications.

2. Experiment Details

AlN piezoelectric thin films were deposited on silicon (100) substrates (0.5 mm thick), 3 × 4 cm 304 stainless steel substrates (0.8 mm thick) and M64 × 270 mm wind turbine bolts via radio frequency (RF) magnetron sputtering. A high-purity aluminum target (99.9999%) with a thickness of 8 mm and a diameter of 150 mm was employed. Prior to film deposition, all substrates underwent sequential ultrasonic cleaning in acetone, ethanol, and deionized water, each for 10 min, to remove organic contaminants and particulate residues. Following cleaning, the substrates were thoroughly dried under a stream of nitrogen and mounted onto the sample holder inside the vacuum chamber. The chamber was then heated to 250 °C, and the base pressure was reduced to 5×10^{-3} Pa. High-purity argon gas (99.99%) was introduced, after which a negative bias voltage (−150 V) and arc power were applied. Substrate surface cleaning was performed via plasma etching for 30 min under the following conditions: duty cycle of 50%, working pressure of 1.0 Pa, and discharge current of 90 A. This step effectively removed native oxides and adsorbed

impurities from the substrate surfaces. Subsequently, a reactive sputtering atmosphere was established by introducing a mixture of argon (90 sccm) and nitrogen (90 sccm), both of 99.99% purity, while maintaining the chamber pressure at 2.0 Pa. RF power was then initiated to commence AlN film growth. Deposition was sustained for 8 h; upon completion, the RF power was switched off, and the sample was allowed to cool to room temperature inside the chamber before removal—thereby minimizing thermal stress and preventing film delamination or cracking. The detailed deposition parameters are summarized in Table 1.

Table 1. Preparation parameters of AlN thin films and AgCr electrode.

Experimental Parameters	AlN Thin Films	AgCr Electrode
Chamber temperature/°C	250	100
Gas pressure/Pa	2.0	1.0
Ar to N ₂ ratio	1:1	1:0
Sputtering time/h	8	1
RF power/W	700, 800, 900	700
Target-to-substrate distance/mm	55, 60, 65, 70, 75	70

X-ray diffraction (XRD) was conducted using a Tongda TDM-10 diffractometer with Cu K α radiation in continuous scanning mode from 20° to 80° (2 θ). Film surface and cross-sectional morphologies were observed by field emission scanning electron microscopy (SEM, TESCAN MIRA 3, TESCAN ORSAY HOLDING, a.s., Brno, Czech Republic), while microregion composition was analyzed via energy dispersive spectroscopy (EDS) at 20 kV. The film thickness was determined from the average value measured at three different positions on the same substrate. The deposition rate was calculated by dividing the average film thickness by the deposition time. AgCr electrode films were fabricated on the surface of AlN films by means of magnetron sputtering. The specific deposition parameters are shown in Table 1. The room-temperature piezoelectric constant d_{33} was measured using the SA1303A tester, (Wuxi ShiAo Technology Co. Ltd., WuXi, China) and the piezoelectric constant d_{33} of the film was determined by averaging the results of five tests on different positions of the film on the same substrate. The ultrasonic signal generated by the AlN piezoelectric film was captured using a custom-assembled ultrasonic pulse receiver. A voltage spike of 200 V was applied to the transducer to excite ultrasonic waves; the sampling accuracy of the equipment's sound is 0.1 ns. These waves propagated through the substrate material, reflected from its bottom surface, and were subsequently detected by the same transducer and converted back into electrical signals. The received pulse–echo signal was recorded with a gain of dB, using a 12.5 MHz low-pass filter and a 60 MHz high-pass filter. The amplitude of the ultrasonic signal generated by the AlN film is calculated by averaging the maximum amplitudes of the three excitation signals at different positions on the same substrate. In the ultrasonic signal analysis, the first reflected echo signal was selected as the characteristic signal for TOF extraction. The TOF was determined by the time corresponding to the peak position of the first echo signal, and the ultrasonic amplitude was defined as the voltage value of this first echo peak. During the temperature and axial-load calibration tests, the time difference was calculated by subtracting the reference TOF under the initial condition from the TOF measured at each temperature or stress level. This method ensured that the temperature- and load-induced variations were evaluated using the same echo feature throughout the calibration process. It should be noted that all reported statistical variations were obtained from repeated measurements at different positions on the same deposited sample. Systematic sample-to-sample or batch-to-batch reproducibility tests were not fully conducted in the present study. A temperature cycling box was used to calibrate the wind turbine bolts. The temperature

range of this temperature cycling box was 10 to 70 °C, with a heating rate of 1 °C per minute. Sampling points were set at each 10 °C interval. The axial force calibration of the bolts was accomplished by applying axial loads using a universal testing machine (WAW-300, Shanghai Precision Instrument and Metering Co. Ltd., Shanghai, China). When the preset force value was reached, the round-trip ultrasonic propagation time within the bolt and the bolt temperature were simultaneously recorded. For the M64 × 270 mm bolts, the calibration range was 0 kN to 1000 kN, and TOF measurements were conducted at intervals of 100 kN.

3. Results and Discussion

3.1. AlN Thin Films Deposited at Different RF Power

3.1.1. Surface Morphology and Chemical Composition

Figure 1 presents the surface and cross-sectional SEM images of AlN films deposited at varying RF sputtering powers (700–900 W). Regarding surface morphology evolution, an increase in RF power induces a clear transition from fine, dispersed particles to densely packed, regularly shaped “pebble-like” grains. At higher RF powers, sputtered atoms impinging on the substrate acquire greater surface migration energy, facilitating atomic rearrangement, coalescence of neighboring nanoscale grains, and subsequent grain growth. Consequently, film porosity decreases markedly, and surface flatness improves significantly. As further evidenced in Figure 1, the average grain size increases progressively with rising RF power, a trend directly attributable to the enhanced kinetic energy of the sputtered species [17]. In the cross-sectional morphology, all samples exhibit a columnar grain structure extending throughout the film thickness. Notably, increasing RF power leads to a substantial increase in film thickness. This behavior can be attributed to the enhanced sputtering rate under higher RF power. In addition, the columnar morphology becomes more apparent at higher RF powers, accompanied by a denser cross-sectional structure.

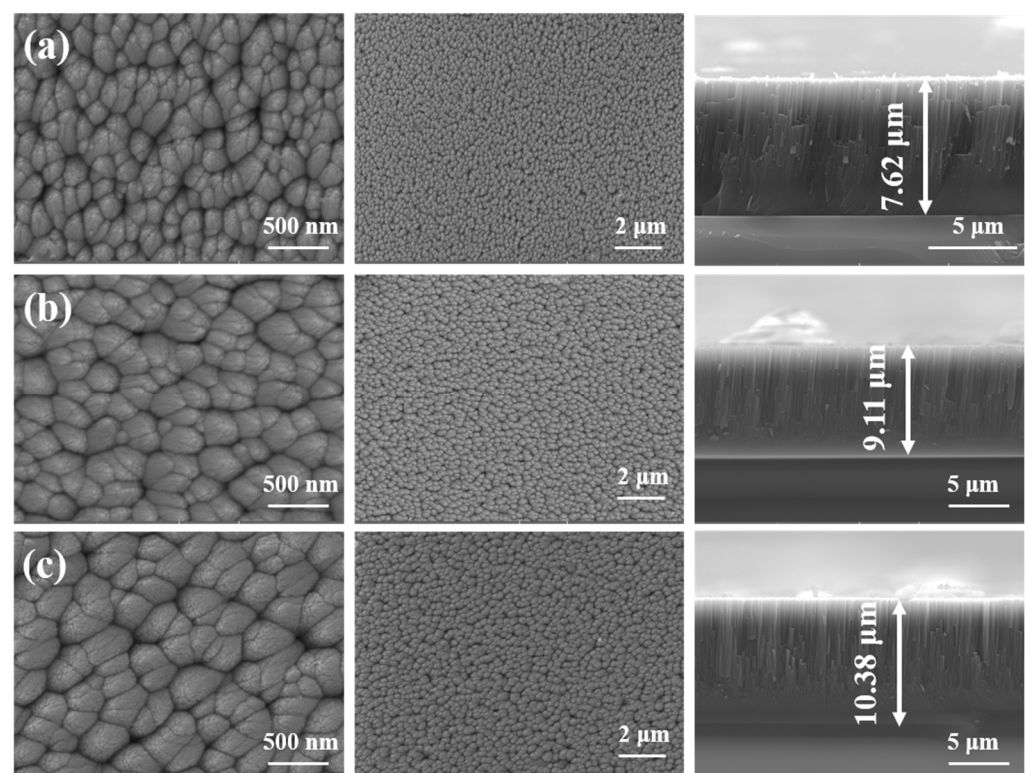


Figure 1. The morphology of AlN thin films under different RF powers: (a) 700 W; (b) 800 W; (c) 900 W.

Figure 2 presents the variation in deposition rate and the corresponding surface elemental composition ratio of AlN films fabricated under different RF powers. As shown in Figure 2a, both film thickness and deposition rate exhibit a clear positive correlation with RF power. This trend is consistent with the fundamental principles of physical vapor deposition (PVD): increasing RF power enhances plasma density and the kinetic energy of argon ions, thereby elevating the sputtering yield from the target surface. Figure 2b shows the EDS spectra of the surface elemental composition of the AlN film under different RF powers. The AlN films consist predominantly of aluminum (Al) and nitrogen (N); however, trace oxygen (O) contamination is inevitably incorporated during deposition. At 700 W, the films contain a relatively high O content (11 at.%) and a low N content (38 at.%), resulting in an Al-rich, N-deficient composition ($\text{Al:N} > 1$). Upon increasing the RF power to 900 W, the oxygen content decreases markedly to 7 at.%, while the nitrogen content rises to 41 at.%; concurrently, the Al content remains stable at approximately 52 at.%, yielding an Al:N ratio approaching the ideal stoichiometric value of 1:1. This compositional evolution can be attributed to the increased ionization rate of the reactive gas (N_2) under higher sputtering power, which promotes the formation of Al-N bonds. Meanwhile, the enhanced bombardment effect of energetic particles facilitates the removal of oxygen-containing species from the growing film surface. It is well known that in the AlN lattice, oxygen atoms are easily substituted for nitrogen atoms to form lattice defects, which seriously weakens the piezoelectric constant and insulation performance of the film [18]. Therefore, the film deposited at 900 W shows relatively lower O content and an Al:N ratio closer to stoichiometry among the tested samples, which may be beneficial for the subsequent electromechanical response.

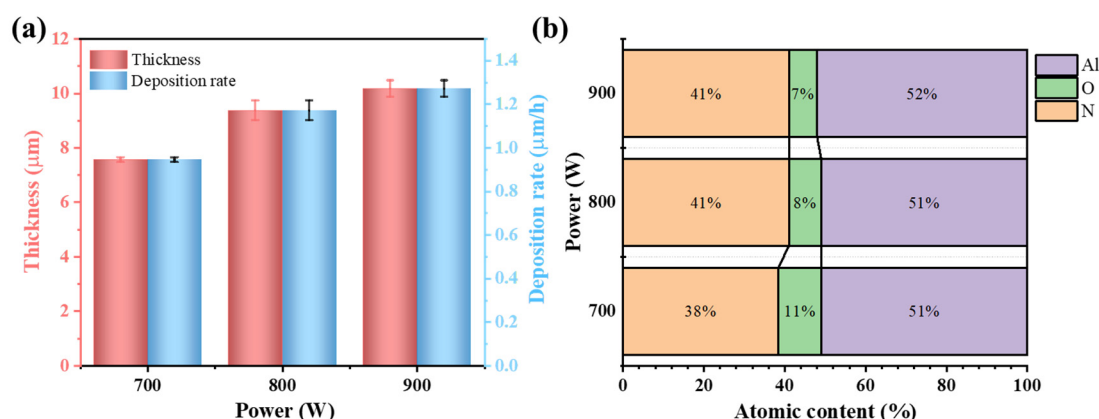


Figure 2. (a) Thickness and deposition rate of AlN films under different RF powers; (b) surface elemental composition.

3.1.2. Crystal Structure

Figure 3a shows the XRD patterns of AlN films prepared under different RF powers. As can be seen from the figure, all samples exhibit an AlN (002) diffraction peak, and the two smaller diffraction peaks within the $40\text{--}50^\circ$ range can be assigned to the stainless steel substrate. The presence of the AlN (002) peak indicates that textured wurtzite AlN films were formed under the RF power range of 700–900 W. With the increase in sputtering power, the (002) diffraction peak of the AlN film shifts slightly to the left, indicating that the residual compressive stress within the plane of the material slightly decreases. The (002) diffraction peak moves to a lower 2θ value direction, which can be used as an indication of the presence of compressive stress in the film [19,20]. Figure 3b summarizes the relative intensity and full width at half maximum (FWHM) of the AlN (002) diffraction peak extracted from the XRD patterns. With the increase in sputtering power from 700 W to 900 W,

the relative intensity of the AlN (002) diffraction peak gradually increases, while the FWHM gradually decreases. According to the periodic bond chain theory and the crystal structure characteristics of AlN, the formation of different crystal planes is affected by the energy of sputtered species during film growth [21]. As the sputtering power increases, the energy of sputtered particles arriving at the substrate also increases, which may promote atomic migration and rearrangement during film growth. This can enhance the diffraction response from the AlN (002) plane, resulting in the increased relative intensity of the AlN (002) diffraction peak. In conclusion, with the increase in power, the intensity of the (002) diffraction peak of the piezoelectric film continuously increases, and the half-width continuously decreases. This indicates that a high sputtering power is conducive to the preparation of high-quality AlN piezoelectric sensing films. Therefore, using a power of 900 W is the most suitable for preparing high-quality piezoelectric films.

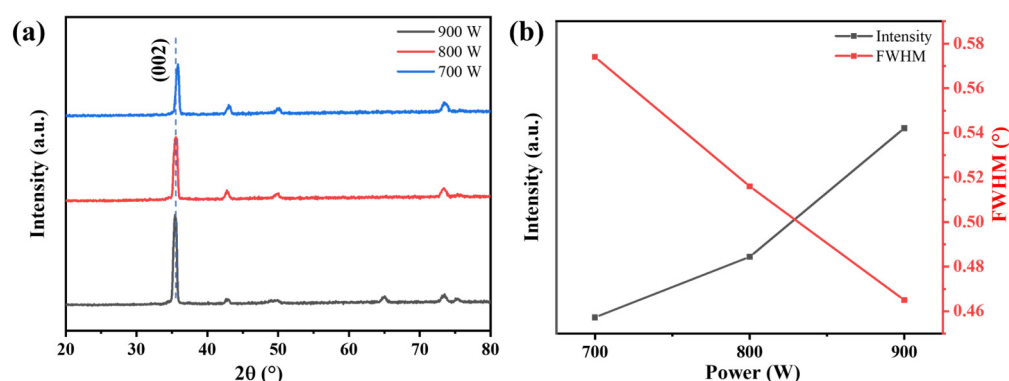


Figure 3. Structure of AlN thin films with different RF powers: (a) XRD patterns; (b) intensity and FWHM of (002) diffraction peak.

3.1.3. Ultrasonic Response

Figure 4 shows the ultrasonic response performance of the AlN film under different RF powers and the situation of its piezoelectric constant d_{33} . The ultrasonic signals excited by the AlN films prepared under different RF powers are shown in Figure 4a. As shown in the figure, all samples are able to generate detectable ultrasonic echo signals. Based on the substrate thickness and the measured round-trip propagation time, the calculated wave velocity corresponds to the longitudinal wave (LW) mode. Among the tested RF powers, the film deposited at 900 W exhibits a higher echo amplitude than those deposited at lower RF powers [22]. Figure 4b shows the piezoelectric constant d_{33} of the AlN films under different RF powers. The measured d_{33} value increases with increasing RF power under the investigated conditions. For the sample deposited at 900 W, the relatively larger film thickness, lower oxygen content, and more compact morphology may contribute to the higher measured d_{33} value and ultrasonic echo amplitude. The variation in ultrasonic echo amplitude is generally consistent with the measured d_{33} values, indicating that the electromechanical response of the films contributes to the observed ultrasonic output. Under the tested RF power range, the film deposited at 900 W showed a dense and continuous columnar structure, reduced oxygen incorporation, stronger AlN (002) diffraction response, and higher ultrasonic output, without obvious cracking or peeling after deposition.

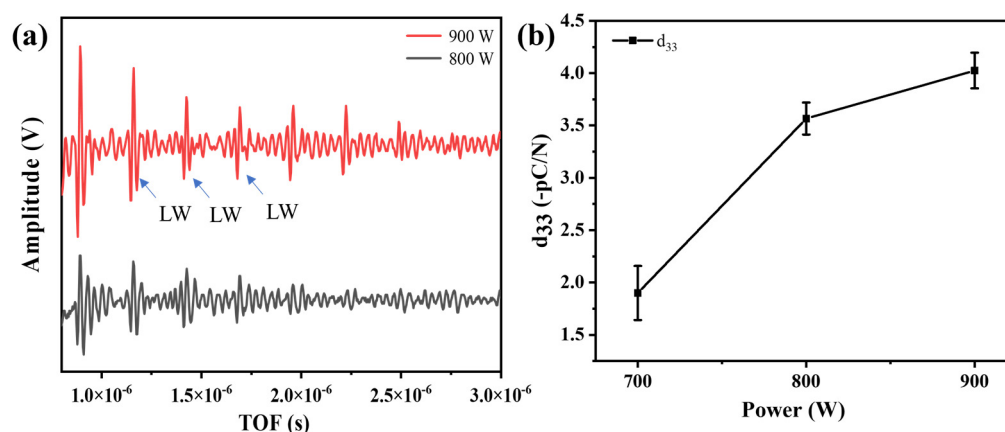


Figure 4. (a) Ultrasonic pulse–echo response of AlN film deposited on SS wafers at different deposition pressures; (b) d_{33} .

3.2. AlN Thin Films Deposited at Different Deposition Distances

3.2.1. Surface Morphology and Chemical Composition

Figure 5 shows the SEM images of AlN piezoelectric thin films deposited at different target-to-substrate distances under an RF power of 900 W, further revealing the influence of deposition distance on film morphology. At the 55 mm condition, the surface morphology of the coating is significantly different from that of the other two coatings. The film surface presents rough and irregular wedge-shaped or elongated grains. This morphology may be related to the shorter transport distance between the target and the substrate, where sputtered species can reach the substrate with relatively higher kinetic energy, leading to stronger particle bombardment and changes in surface nucleation behavior [23]. When the distance increases to 60 mm, as shown in Figure 5b, the surface becomes more compact, and the grains exhibit relatively uniform and rounded “pebble-like” features. Further increasing the distance to 65–75 mm (Figure 5c–e), the surface grains still maintain the “pebble-like” shape, but the grain size decreases as the distance increases. This is because the longer distance increases the probability of gas-phase collisions during the particle transmission, resulting in the attenuation of the kinetic energy of the adsorbed atoms reaching the substrate and a decrease in surface migration ability. Combined with the enlarged cross-sectional view, the cross-section of the AlN film shows a clear columnar crystal growth structure. At a deposition distance of 55 mm, the cross-sectional morphology appears less regular than that of the films deposited at 60–70 mm. This may be associated with stronger bombardment effects at the shorter target-to-substrate distance. When the deposition distance is 60–70 mm, the cross-section of the prepared sample presents clear columnar crystal outlines with uniform sizes. It can be observed that at 60 mm, the grain diameter is the largest, and the columnar crystals extend from the matrix to the surface of the film. When the deposition distance further increases to 75 mm, the grains of the film become smaller, resulting in an indistinct columnar crystal structure of the film.

Figure 6 shows the thickness of the AlN film, the deposition rate (Figure 6a), and the distribution of surface element atomic percentages (Figure 6b) at different deposition distances. As the target-to-substrate distance increases from 55 mm to 75 mm, the film thickness and deposition rate show a trend of first increasing and then decreasing, reaching a peak at 60 mm. When the distance is shortened to 55 mm, the resputtering effect of the film is enhanced, resulting in a decrease in the deposition rate. As the deposition distance increases to 60 mm, the resputtering effect of the thin film weakens, resulting in an increase in the deposition rate of the film. As the distance further increases to 65–75 mm, gas-phase scattering during particle transport becomes more likely, which can reduce the effective flux and kinetic energy of sputtered species arriving at the substrate. As shown

in Figure 6b, AlN films are mainly composed of Al and N, with a small amount of O. At 55 mm, although the oxygen content is low (4%), the nitrogen content decreases (42%), which may be caused by the high-energy particles bombarding at a short distance, resulting in the preferential desorption of lighter nitrogen atoms from the film surface. At a distance of 60 mm, the N content of the film reaches the highest (46%), the Al content is 49%, and both are closest to the ideal stoichiometric ratio; the oxygen content remains at a relatively low level (5%). As the deposition distance increases, the oxygen impurity content in the film rises. This indicates that a larger target-base distance will result in a decrease in the effective nitrogen active particles reaching the substrate surface. At the same time, due to the reduced deposition flux and the extended particle transmission path, the influence of residual oxygen or water vapor and other oxygen-containing impurities on the surface composition of the film becomes stronger.

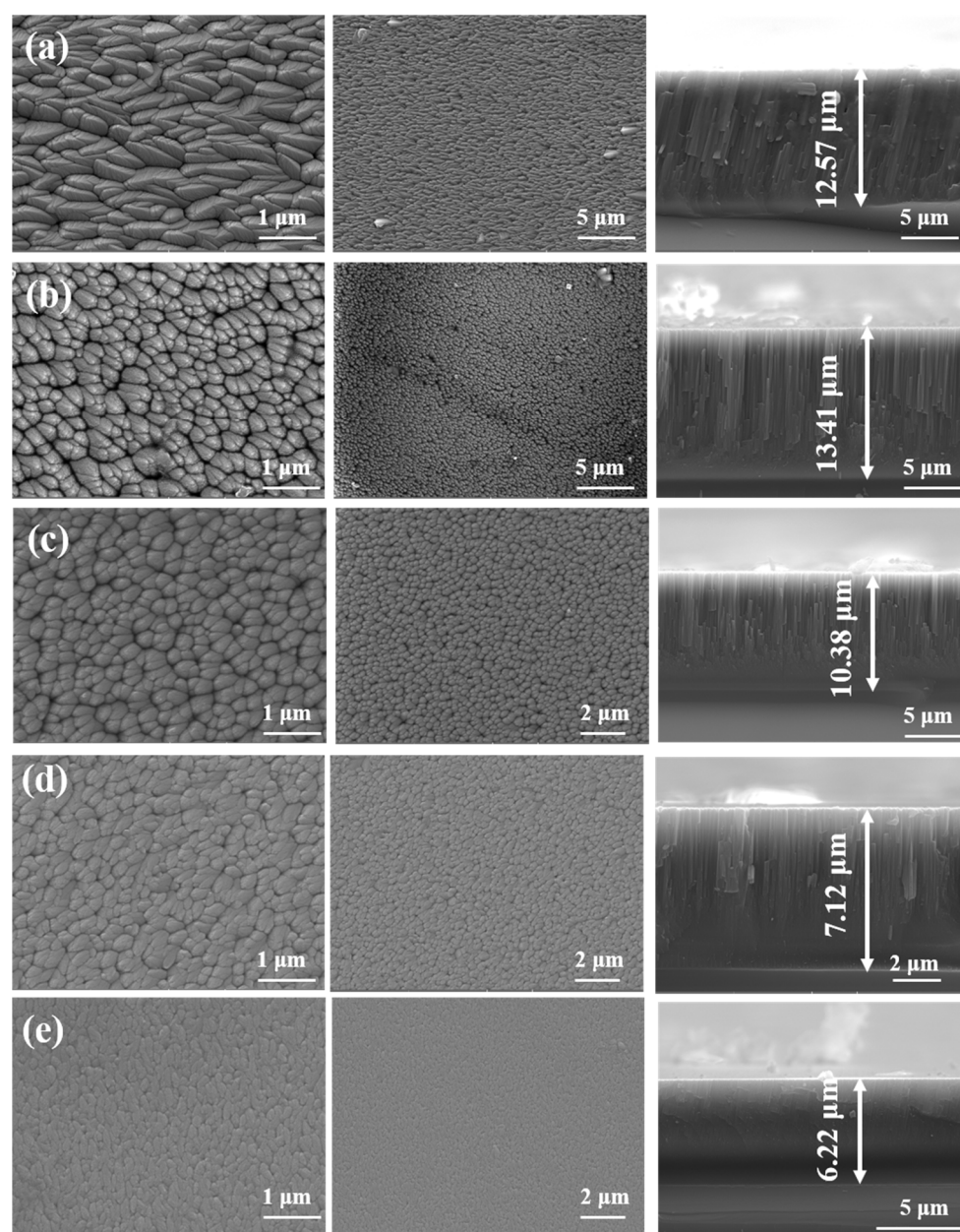


Figure 5. The morphology of AlN thin films deposited on Si wafers under different distances: (a) 55 mm; (b) 60 mm; (c) 65 mm; (d) 70 mm; (e) 75 mm.

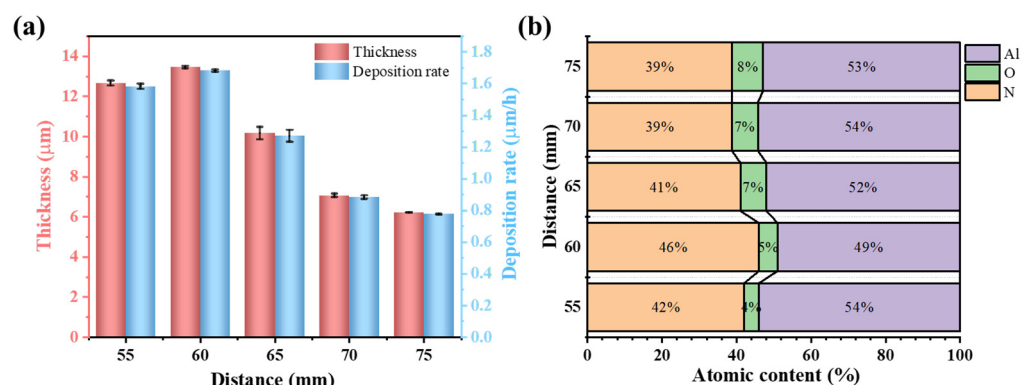


Figure 6. (a) Thickness and deposition rate of AlN films under different distances; (b) surface elemental composition.

3.2.2. Crystal Structure

Figure 7a shows the XRD patterns of AlN films deposited at different target-to-substrate distances. All films exhibit a diffraction peak at approximately 36° , which can be assigned to the AlN (002) plane, indicating the formation of textured wurtzite AlN films under the investigated conditions. At 55 mm, a weak diffraction feature corresponding to AlN (103) is also observed. This weak AlN (103) feature may be associated with the altered incidence and transport behavior of sputtered species at the shorter target-to-substrate distance [23,24]. As the distance increases, the (002) diffraction peak of the AlN film shifts slightly to the right, indicating that the residual compressive stress within the material plane has been released. Figure 7b summarizes the relative intensity and FWHM of the AlN (002) peak as a function of target-to-substrate distance. The film deposited at 60 mm exhibits a relatively intense AlN (002) diffraction peak compared with the other tested distances. When the target-to-substrate distance is further increased to 65–75 mm, the relative intensity of the AlN (002) peak decreases. This variation may be related to increased gas-phase scattering during particle transport, which can reduce the effective flux and kinetic energy of sputtered species arriving at the substrate. Such changes may affect the film growth behavior and the resulting diffraction response. In addition, the decrease in film thickness at larger distances, as shown in Figure 6a, may also contribute to the reduced XRD peak intensity. The FWHM shows a non-monotonic variation with target-to-substrate distance, increasing from 55 mm to 65 mm and then decreasing at larger distances, with a lower value observed at 75 mm. The FWHM value can be influenced by multiple factors, including film thickness, microstructural evolution, defects, and instrumental broadening.

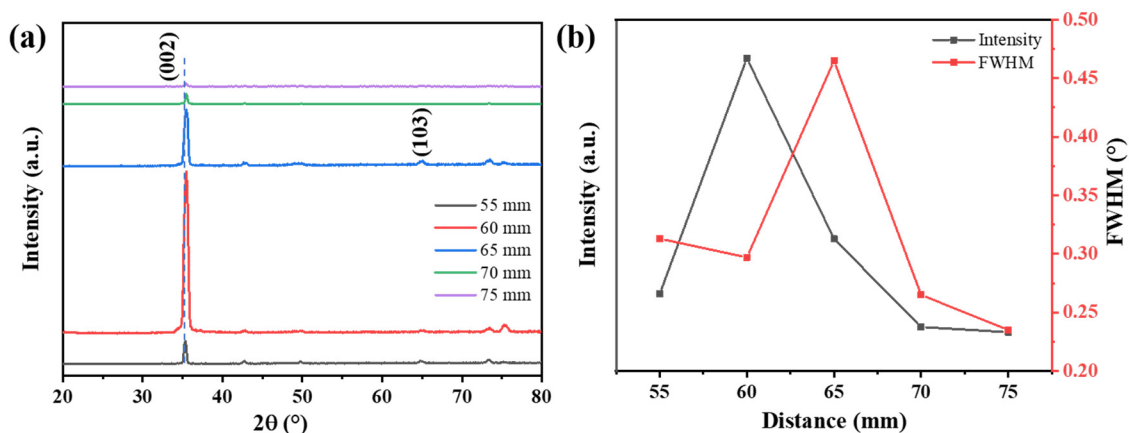


Figure 7. Structure of AlN thin films with different distances (a) XRD patterns; (b) intensity and FWHM of (002) diffraction peak.

3.2.3. Ultrasonic Response

Figure 8a shows the stimulated ultrasonic time-domain echo signals of AlN films prepared under different target substrate distances. From the type of the excitation ultrasonic signal, samples prepared under different target substrate distances can all generate ultrasonic longitudinal wave signals. However, when the target substrate distance is 55 mm, the preparation of the piezoelectric coating not only generates ultrasonic longitudinal waves but also ultrasonic transverse waves. This is related to the fact that the columnar crystal structure of the film under this condition is not completely perpendicular to the substrate but grows at an inclined angle [25]. Figure 8b is the spectrum of the AlN film at a distance of 55 mm. This waveform presents a wide-band narrow-pulse echo signal, with a center frequency of approximately 26 MHz, still showing the characteristics of a high-frequency ultrasonic transducer. The maximum signal amplitude and center frequency of the ultrasonic echo of the AlN film at different distances are shown in Figure 8c. As the distance increases, the amplitude of the ultrasonic signal excited by the film first increases and then decreases, reaching the maximum relative amplitude at a deposition distance of 60 mm. All films at different distances show a high-frequency center frequency greater than 10 MHz. Figure 8d shows the piezoelectric constant d_{33} of the AlN film at different distances. With increasing target-to-substrate distance, the measured d_{33} value first increases and then decreases, with a higher value observed at 60 mm among the tested samples. This variation may be influenced by multiple factors, including film thickness, composition, morphology, and crystallographic texture [26]. The d_{33} piezoelectric constant of the AlN film prepared at 60 mm is close to the theoretical piezoelectric constant value of AlN.

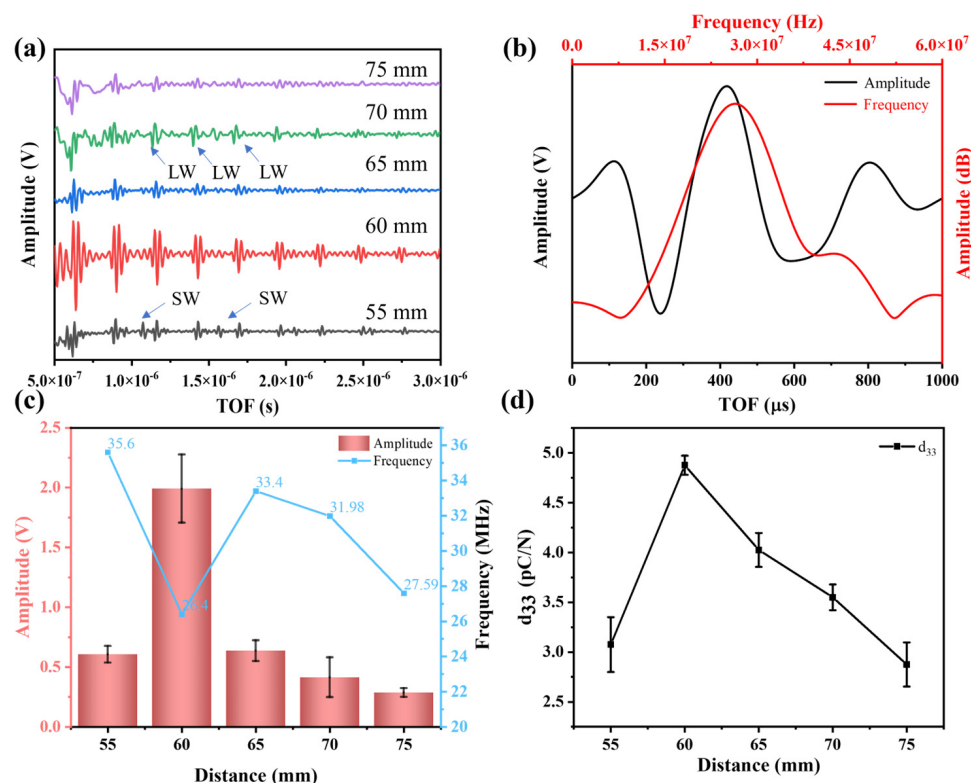


Figure 8. (a) Ultrasonic pulse-echo response of AlN film deposited on SS wafers at different distances; (b) spectral diagram at 60 mm; (c) relative amplitude and frequency; (d) d_{33} .

3.3. Application of AlN Thin-Film Transducer for Bolt

To evaluate the applicability of the AlN thin-film transducer for bolt preload measurement, an AlN thin-film transducer was deposited on an M64 × 270 mm bolt using the selected deposition conditions of 900 W RF power and a target-to-substrate distance of 60 mm. Compared with the other tested conditions, the film prepared at 900 W and 60 mm showed a denser columnar morphology, a stronger AlN (002) diffraction peak intensity, a higher d_{33} value, and a higher longitudinal ultrasonic echo amplitude. In practical bolt preload detection, especially for large wind turbine bolts, the ultrasonic wave needs to propagate over a relatively long distance and experience reflection attenuation inside the bolt. A higher initial echo amplitude is therefore important for maintaining a sufficient signal-to-noise ratio and ensuring reliable TOF extraction under industrial testing conditions. Since the length of the bolt is much longer than the thickness of the stainless steel sheet, to reduce the attenuation of the ultrasonic signal, the deposition time of the AlN film on the bolt was extended to 10 h. To calibrate the temperature, acoustic time sampling was conducted on bolts of different temperatures under no-load conditions, with the sampling temperature range being 10–70 °C, and sampling was carried out approximately every 10 °C. The results are shown in Figure 9a. By calculating the echo time of the ultrasonic wave, its sound speed is 5876 m/s, which is consistent with the sound speed of the ultrasonic longitudinal wave. As the temperature increases, the measured TOF increases, which is generally associated with thermal expansion of the bolt and the temperature dependence of ultrasonic velocity. Linear fitting of the temperature–TOF data shows a strong linear relationship, with $R^2 > 99.99\%$. To evaluate the relationship between ultrasonic TOF and axial load, TOF measurements were conducted under different axial loads at 11.5 °C, as shown in Figure 9b. As the axial load increases, the TOF of the ultrasonic echo will be delayed. This is mainly caused by two factors: one is that the overall length of the bolt will change under the force condition, thereby causing an increase in the propagation distance of the ultrasonic wave; the other is that according to the acoustic elasticity theory, the ultrasonic longitudinal wave is more sensitive to forces parallel to the propagation direction, so in the axial tensile stress condition, the ultrasonic propagation speed will decrease [27–29]. Through the linear fitting of axial load and TOF, a strong correlation was shown, with an R^2 value greater than 99.99%. To verify the accuracy of this ultrasonic method for axial stress in bolts, the absolute and relative error values of the bolts under different loads were calculated. The results are shown in Figure 9c. The results indicate that as the load increases, the absolute load error remains within the ± 7 kN range. These results demonstrate the potential of the deposited AlN thin-film transducer for bolt preload measurement under the tested conditions. Further work is needed to evaluate deposition reproducibility and long-term performance under practical service conditions. The directly deposited AlN thin-film transducer is expected to provide improved coupling stability because it avoids the adhesive layer and coupling agent used in conventional bonded piezoelectric patches. The high mechanical strength, chemical stability, and acoustic velocity of AlN are also favorable for ultrasonic sensing under mechanical and thermal loading. In this study, clear ultrasonic echoes were maintained during temperature calibration from 10 to 70 °C and axial-load calibration from 0 to 1000 kN, suggesting functional stability under the tested conditions.

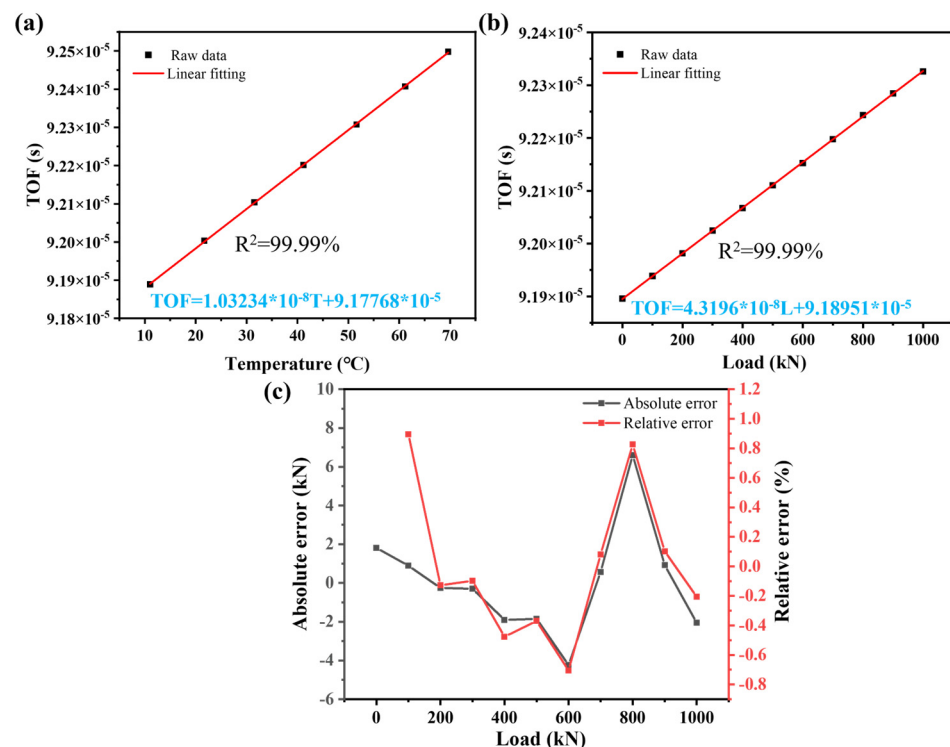


Figure 9. AIN thin-film transducers deposited on bolts. (a) Relationship between temperatures and TOF at 0 kN; (b) relationship between loads and TOF at 11.5 °C; (c) relative error and absolute error of load.

4. Conclusions

In this study, AIN thin films were prepared by radio frequency magnetron sputtering, and the effects of RF power and target-to-substrate distance on film growth behavior, morphology, crystal structure, piezoelectric response, and ultrasonic response were investigated. Within the tested RF power range, increasing the RF power increased the film thickness and deposition rate, reduced the O content on the film surface, and increased the intensity of the AIN (002) diffraction peak. The film deposited at an RF power of 900 W was able to generate ultrasonic longitudinal wave echoes with a higher signal amplitude. The target-to-substrate distance also had an evident influence on the deposition behavior and ultrasonic response of the AIN films. As the target-to-substrate distance increased, the deposition rate first increased and then decreased. Among the investigated distances, the film deposited at 60 mm showed a relatively intense AIN (002) diffraction peak intensity, a higher ultrasonic echo amplitude, and a higher measured piezoelectric coefficient d_{33} . To evaluate the applicability of the AIN thin-film transducer for bolt preload measurement, an AIN thin-film transducer was deposited on an M64 × 270 mm bolt. The temperature calibration results showed a linear relationship between temperature and TOF under the no-load condition. Based on acoustoelastic theory, the axial load calibration results also showed a strong linear relationship between TOF and axial load, with $R^2 > 99.99\%$ under the tested conditions. The preload measurement error remained relatively small within the tested load range, indicating the potential of the deposited AIN thin-film transducer for bolt preload measurement. Further work is needed to evaluate deposition reproducibility and long-term performance under practical service conditions.

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review & editing, Y.J.; Supervision, J.Z. and B.Y.; Funding acquisition, B.Y. All authors have read and agreed to the published version of the manuscript.

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References

1. Han, J.; Xie, K.; Yang, Z.; Li, L.A.; Zhao, M. A Study of the Nonlinear Attenuation Behavior of Preload in the Bolt Fastening Process for Offshore Wind Turbine Blades Using Ultrasonic Technology. *Energies* **2025**, *18*, 3211. [CrossRef]
2. Lochan, S.; Mehmanparast, A.; Wintle, J. A review of fatigue performance of bolted connections in offshore wind turbines. *Procedia Struct. Integr.* **2019**, *17*, 276–283. [CrossRef]
3. Zeng, X.; Zhang, X.; Pelenovich, V.; Neena, D.; Xu, C.; Liu, Y.; Jiang, Y.; Zeng, L.; Pogrebnyak, A.; Vildanov, R.J.C.I. High-temperature thin film lithium niobium oxide transducers for bolts. *Ceram. Int.* **2023**, *49*, 7710–7716. [CrossRef]
4. Wang, T.; Song, G.; Liu, S.; Li, Y.; Xiao, H. Review of Bolted Connection Monitoring. *Int. J. Distrib. Sens. Netw.* **2013**, *9*, 871213. [CrossRef]
5. Yadavar, N.S.M.; Masoud, G. A Review Paper on Looseness Detection Methods in Bolted Structures. *Lat. Am. J. Solids Struct.* **2017**, *14*, 2153–2176. [CrossRef]
6. Garcia, M.; Jairo, A. A Novel Ultrasonic Method to Quantify Bolt Tension. Ph.D. Thesis, University of South Florida, Tampa, FL, USA, 2012.
7. Miao, R.; Shen, R.; Zhang, S.; Xue, S. A Review of Bolt Tightening Force Measurement and Loosening Detection. *Sensors* **2020**, *20*, 3165. [CrossRef] [PubMed]
8. Ali, W.R.; Prasad, M.J.S.; Physical, A.A. Piezoelectric MEMS based acoustic sensors: A review. *Sens. Actuators A Phys.* **2020**, *301*, 111756. [CrossRef]
9. Wang, Z.; Wang, C.; Liu, L. Design and analysis of a PZT-based micromachined acoustic sensor with increased sensitivity. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control.* **2005**, *52*, 1840–1850. [CrossRef] [PubMed]
10. Xu, T.; Wu, G.; Zhang, G.; Hao, Y. The compatibility of ZnO piezoelectric film with micromachining process. *Sens. Actuators A Phys.* **2003**, *104*, 61–67. [CrossRef]
11. Hou, R.; Hutson, D.; Kirk, K.J. Development of sputtered AlN thin-film ultrasonic transducers for durable high-temperature applications. *Insight-Non-Destr. Test. Cond. Monit.* **2013**, *55*, 302–307.
12. Hou, R.; Hutson, D.; Kirk, K.J.; Fu, Y.Q. AlN thin film transducers for high temperature non-destructive testing applications. *J. Appl. Phys.* **2012**, *111*, 074510. [CrossRef]
13. Hou, R.; Hutson, D.; Kirk, K.J. Investigation of thin-film ultrasonic transducers for high-temperature applications. *Insight-Non-Destr. Test. Cond. Monit.* **2012**, *54*, 68–71.
14. Ababneh, A.; Schmid, U.; Hernando, J.; Sánchez-Rojas, J.; Seidel, H. The influence of sputter deposition parameters on piezoelectric and mechanical properties of AlN thin films. *Mater. Sci. Eng. B* **2010**, *172*, 253–258. [CrossRef]
15. Khanna, A.; Bhat, D.G. Effects of deposition parameters on the structure of AlN coatings grown by reactive magnetron sputtering. *J. Vac. Sci. Technol. A* **2007**, *25*, 557–565. [CrossRef]
16. Iriarte, G.F.; Rodríguez, J.; Calle, F. Synthesis of c-axis oriented AlN thin films on different substrates: A review. *Mater. Res. Bull.* **2010**, *45*, 1039–1045.
17. Jiang, Y.; Jing, X.; Li, J.; Zeng, X.; Pelenovich, V.; Xu, C.; Xiong, Z.; Zhang, J.; Yang, B. Extreme High temperature Tolerant AlN thin film ultrasonic transducer and its application for bolt preload measurement. *J. Alloys Compd.* **2025**, *1027*, 180498. [CrossRef]
18. Vergara, L.; Clement, M.; Iborra, E.; Sanz-Hervás, A.; López, J.G.; Morilla, Y.; Sangrador, J.; Respaldiza, M.A. Influence of oxygen and argon on the crystal quality and piezoelectric response of AlN sputtered thin films. *Diam. Relat. Mater.* **2004**, *13*, 839–842. [CrossRef]
19. Guo, Q.; Li, D.; Hua, Q.; Ji, K.; Wang, Z.L. Enhanced Heat Dissipation in Gallium Nitride-Based Light-Emitting Diodes by Piezo-phototronic Effect. *Nano Lett.* **2021**, *21*, 4062–4070. [PubMed]

20. Sun, W. Temperature Dependence of Stress and Optical Properties in AlN Films Grown by MOCVD. *Nanomaterials* **2021**, *11*, 698. [[CrossRef](#)]
21. Xu, X.H.; Wu, H.S.; Zhang, C.J.; Jin, Z.H. Morphological properties of AlN piezoelectric thin films deposited by DC reactive magnetron sputtering. *Thin Solid Film.* **2001**, *388*, 62–67. [[CrossRef](#)]
22. Jiang, Y.; Li, J.; Jiao, G.; Li, W.; Liu, Y.; Wang, C.; Xia, B.; Wan, B.; Zhang, J.; Pelenovich, V. ZnO piezoelectric coatings used for the ultrasonic excitation of longitudinal-transverse waves and their application for smart bolts. *J. Vac. Sci. Technol. B* **2022**, *40*, 043002.
23. Xu, C.; Zeng, X.; Zhang, X.; Lv, T.; Jiang, Y.; Wang, Z.; Ma, X.; Ding, Y.; Zhang, J.; Yang, B. Performance optimization of AlN ultrasonic thin-film sensors deposited by RF magnetron sputtering. *Ceram. Int.* **2024**, *50*, 55972–55978. [[CrossRef](#)]
24. Bakri, A.; Nafarizal, N.; Abu Bakar, A.; Megat Hasnan, M.; Raship, N.; Wan Omar, W.; Azman, Z.; Mohamed Ali, R.; Majid, W.A.; Ahmad, M. Electrical and structural comparison of (100) and (002) oriented AlN thin films deposited by RF magnetron sputtering. *J. Mater. Sci. Mater. Electron.* **2022**, *33*, 12271–12280. [[CrossRef](#)]
25. Wingqvist, G. AlN-based sputter-deposited shear mode thin film bulk acoustic resonator (FBAR) for biosensor applications—A review. *Surf. Coat. Technol.* **2010**, *205*, 1279–1286. [[CrossRef](#)]
26. Olivares, J.; González-Castilla, S.; Clement, M.; Sanz-Hervás, A.; Vergara, L.; Sangrador, J.; Iborra, E. Combined assessment of piezoelectric AlN films using X-ray diffraction, infrared absorption and atomic force microscopy. *Diam. Relat. Mater.* **2007**, *16*, 1421–1424. [[CrossRef](#)]
27. Huang, J.; Liu, J.; Gong, H.; Deng, X. A comprehensive review of loosening detection methods for threaded fasteners. *Mech. Syst. Signal Process.* **2022**, *168*, 108652. [[CrossRef](#)]
28. Zhao, X.-X.; Li, Y.-M.; Liu, X.-G.; Yao, K.J. Ultrasonic measurement on axial force of high-strength bolt in service. *J. Low Freq. Noise Vib. Act. Control* **2020**, *39*, 596–603.
29. Liu, W.; Shan, L.; Lin, Z.; Wan, B.; Yang, B.; Zeng, X.; Yang, B.; Pelenovich, V. Dual-Wave ZnO Film Ultrasonic Transducers for Temperature and Stress Measurements. *Sensors* **2024**, *24*, 5691. [[CrossRef](#)] [[PubMed](#)]

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