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Correlation of Target and Substrate Rotation Speeds on the Growth of Aluminum Nitride Thin Film Using an Industrial-Grade Sputtering System

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ABSTRACT

Aluminum Nitride (AlN) thin films are widely used in microelectronics, piezoelectric sensors, and high-power devices because of their good electrical, mechanical, and thermal properties. Among various deposition methods, radio frequency (RF) magnetron sputtering is considered advantageous due to its ability to fabricate homogeneous, high-quality layers with strong adhesion. However, achieving optimal film properties in large-scale deposition, particularly with industrial-grade 12-inch sputtering targets, requires precise control over process parameters, including target and substrate rotation. While rotation dynamics significantly influence film thickness, surface topology, and crystallinity properties, their effects in large-area deposition remain insufficiently explored. This study examines how target/substrate rotation speeds (10/5, 15/5, 0/0, 5/5, 10/10, 5/10, and 5/15 rpm) affect the film thickness, surface topology, and crystallinity characteristics of AlN thin films. The results show that balanced rotation, especially at 10/10 rpm, produces films with superior thickness uniformity and crystallinity, making it optimal for large-area AlN deposition. Therefore, these findings offer valuable insights into improving AlN film quality for larger wafer sizes in industrial applications.

Keywords: *AlN, RF magnetron sputtering, Target and substrate rotation*

1. INTRODUCTION

Expanding on the significance of aluminium nitride (AlN) thin films, they have recently gained recognition because of their exceptional electrical, mechanical, and thermal performances. These characteristics make AlN an ideal candidate for numerous high-performance applications, including but not limited to microelectronic devices, surface acoustic and bulk acoustic wave resonators, piezoelectric sensors, optoelectronics, and high-power electronic devices [1], [2]. One of the key attributes that contributes to its growing prominence in these fields is its wide bandgap of approximately 6.2 eV, which ensures superior electrical insulation and stability under high-power and high-temperature conditions. Moreover, AlN exhibits a high thermal conductivity of approximately 320 W/mK, which enables efficient heat dissipation and makes it suitable for thermal management applications, particularly in power electronics and high-frequency devices [3]. The excellent piezoelectric response of AlN further enhances its utility in sensor and resonator technologies, where precise signal transduction and frequency control are required. Additionally, its strong chemical and thermal stability allows it to withstand harsh environmental conditions, making it a preferred choice for applications that demand long-term reliability and resistance to oxidation and corrosion [4].

Despite these advantages, achieving high-quality AlN thin films with well-controlled film thickness, surface topology and crystallinity properties remains a significant challenge, particularly when scaling from laboratory-scale depositions to large-area industrial production. The fabrication technique reveals a significant role in determining the final film quality, as different methods exhibit variations in film properties. Various methods have been successfully explored to grow AlN films, including metal-organic chemical vapor deposition [5], molecular beam epitaxy [6], and pulsed laser deposition [7]. While these fabrication methods have demonstrated the capability to produce high-quality films, they often suffer from limitations such as high processing temperatures, complex equipment requirements, high production costs, and are suitable for small wafer sizes [8]–[11]. In contrast, radio frequency (RF) magnetron sputtering has received widespread attention because of its capability to fabricate dense and uniform films with strong adhesion to the substrate. This technique offers several advantages, including precise control over deposition parameters, high deposition rates, and compatibility with large-area substrates, making it particularly attractive for research and industrial applications [12], [13].

Achieving high-quality AlN films requires precise control over various deposition parameters. Among these, substrate and target rotation significantly influence film thickness, surface roughness, and crystallinity [14]. However, research on the effects of rotation, especially in industrial-scale deposition using 12-inch sputtering targets, remains limited. Rotation dynamics impact the distribution of sputtered species, plasma density, and overall film growth, all of which affect film consistency and performance [15], [16]. Previous studies have examined substrate rotation in smaller sputtering systems. For example, Bakri *et al.* investigated AlN deposition using a 3-inch target in an RF magnetron sputtering system on 4-inch silicon wafers, comparing static and rotating conditions. Their results showed that substrate rotation affects the crystallographic orientation of AlN films, enabling controlled growth of (100) and (002) peaks [17]. This finding underscores the critical role of rotation in shaping film crystallinity. Luo *et al.* used a 12-inch aluminum target for AlN deposition, but their study focused on optimizing resonator design to reduce anchor loss and improve quality factors rather than examining how a larger target size influences film growth properties [18]. As a result, the impact of large sputtering targets on film properties remains an open question, highlighting the need for further investigation into rotation effects in industrial-grade sputtering systems for the deposited AlN thin film.

Therefore, a systematic investigation of target and substrate rotation speeds is necessary to identify how different rotation speeds affect the film thickness, topology, and structural properties of AlN films produced by a 12-inch RF magnetron sputtering system. By examining a range of rotation speeds, this work aims to determine the best conditions to obtain high-quality AlN films that meet the demands of industrial-scale applications.

2. METHODOLOGY

Before the deposition process, the 2 x 2 cm Si(111) n-type wafers are cleaned using a 5% hydrofluoric acid (HF) solution and diluted with deionized water (DIW) in a 0.05:1 ratio. This cleaning step effectively removes the native silicon dioxide (SiO_2) layer that naturally forms on the surface of Si wafers when exposed to air, along with other contaminants [19]. AlN is then deposited onto the cleaned wafers using a 12” RF magnetron sputtering system (Leader of Advanced Technology, LAT Co., Ltd., Korea) with a rotating magnet behind the aluminum (Al) target, mentioned as “target rotation” from hereafter. The high-purity Al target is sputtered using high-purity argon (Ar) and nitrogen (N_2) gases. The specific deposition settings are listed in Table 1.

Filmetrics F20 thin-film analyzer measures AlN layer thickness. The Atomic Force Microscopy (AFM) is measured using Park Systems XE-100 through non-contact mode. The scan area measured is 1 μm x 1 μm. X-ray diffraction (XRD) is also carried out by a Rigaku SmartLab system with CuKα radiation (40 kV and 30 mA) to observe the structural characteristics of the AlN buffer layer.

Table 1 Deposition parameter

Parameter	Value
RF power	600 W
Background pressure	1 x 10^{-6} Torr
Working pressure	3 mTorr
Ar/N_2 flow rate	70/100 sscm
Deposition time	60 minutes
Target to substrate distance	90 mm
Target/substrate rotation	10/5, 15/5, 0/0, 5/5, 10/10, 5/10, and 5/15 rpm
Process temperature	25 ^{0}C (RT)

3. RESULT AND DISCUSSION

3.1. Film Thickness

The deposited AlN films are presented in **Error! Reference source not found.**. To better interpret the results, the target/substrate rotation parameter is categorized into three distinct regions: Region I (target rotation speed > substrate rotation speed), Region II (target rotation speed = substrate rotation speed), and Region III (target rotation speed < substrate rotation speed). Based on this picture, the uniform color is obtained at a 10/10 rpm setting.

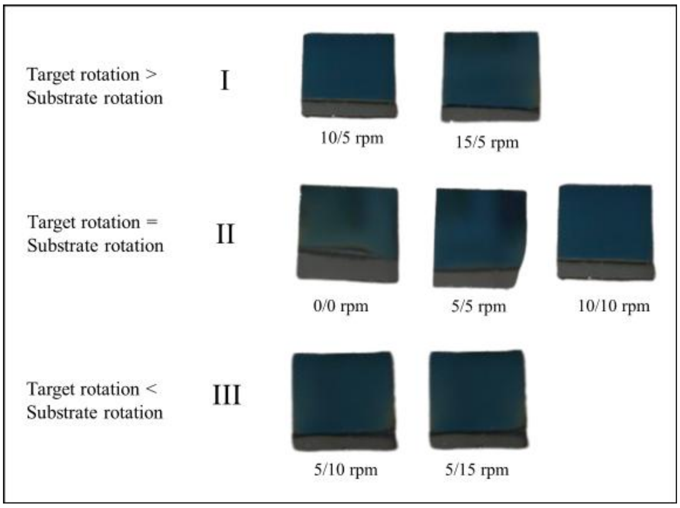


Figure 1. The deposited AlN film.

The AlN film thickness is depicted in **Error! Reference source not found.**(a). In Region II (0/0, 5/5, and 10/10 rpm), the film thickness remains relatively consistent, with only minor fluctuations between 113.63 nm and 108.16 nm, resulting in a small deviation of ±2.77 nm. In contrast, Regions I and III, which involve unbalanced rotation speeds (10/5, 15/5, 5/10, 5/15 rpm), exhibit greater thickness variation of 101.43 - 86.07 nm, with a higher deviation of ±6.57 nm.

The deposition rate follows a similar trend, as depicted in **Error! Reference source not found.**(b), reinforcing the correlation between film thickness and deposition rate. The deposition rate is calculated using Equation 1 [20]. Additionally, **Error! Reference source not found.**(c) illustrates the effect of rotation speed on film thickness uniformity. Thickness uniformity is quantified using the Coefficient of Variation (CoV), as defined in Equation 2, where a lower CoV indicates higher uniformity [21].

$$Deposition\ rate: \frac{Film\ thickness\ (nm)}{Deposition\ time\ (minutes)} \tag{1}$$

$$CoV = \frac{deviation\ (nm)}{average\ thickness\ (nm)} \times 100\% \tag{2}$$

As shown in **Error! Reference source not found.**(c), higher target/substrate rotation rates, such as 10/10 rpm, result in more uniform plasma exposure, enhancing thickness homogeneity. This result correspondence with the film color in Figure 1. However, the wider spread of deposited atoms leads to a lower overall film thickness compared to lower or zero rotation conditions. In contrast, at lower or no rotation speeds (0/0 and 5/5 rpm), a higher CoV indicates that thickness uniformity deteriorates. The direct sputtering effect causes localized thickening due to limited lateral atom distribution, leading to a higher deposition rate but increased non-uniformity [22], [23]. The films exhibit asymmetric thickness distribution for unbalanced rotation settings (10/5, 15/5, 5/10, and 5/15 rpm), further compromising uniformity. Among all tested conditions, 10/10 rpm provides the most uniform film, making it the optimal choice for scaling up to larger wafer sizes.

3.2. Topological Properties

Figure **3** presents the AFM results for different target/substrate rotation speeds, while
Figure **4** illustrates the correlation between rotation speed, root mean square (RMS) roughness, and grain size. The results indicate that surface roughness decreases as the target and substrate rotation increase while grain size increases. This trend is consistent with previous studies, which suggest that higher rotational speeds promote more uniform deposition and larger grain formation due to enhanced atomic mobility during film growth [24]. In Region II, further increasing the rotation speed allows for a decrease in both surface roughness and grain size.

3.3. Structural Properties

Figure **5**(a) presents the XRD graph of AlN deposited under various target/substrate rotation settings. The (002) peak intensity fluctuates across these conditions, reflecting variations in the film's crystallinity. The strongest (002) peak is observed at 5/5 rpm, indicating a well-oriented c-axis growth, which is essential for high-quality AlN. In contrast, the 0/0 rpm condition results in a significantly weaker (002) peak, suggesting poor crystallinity. This is likely due to the lack of substrate rotation, leading to non-uniform film growth and increased internal stress.

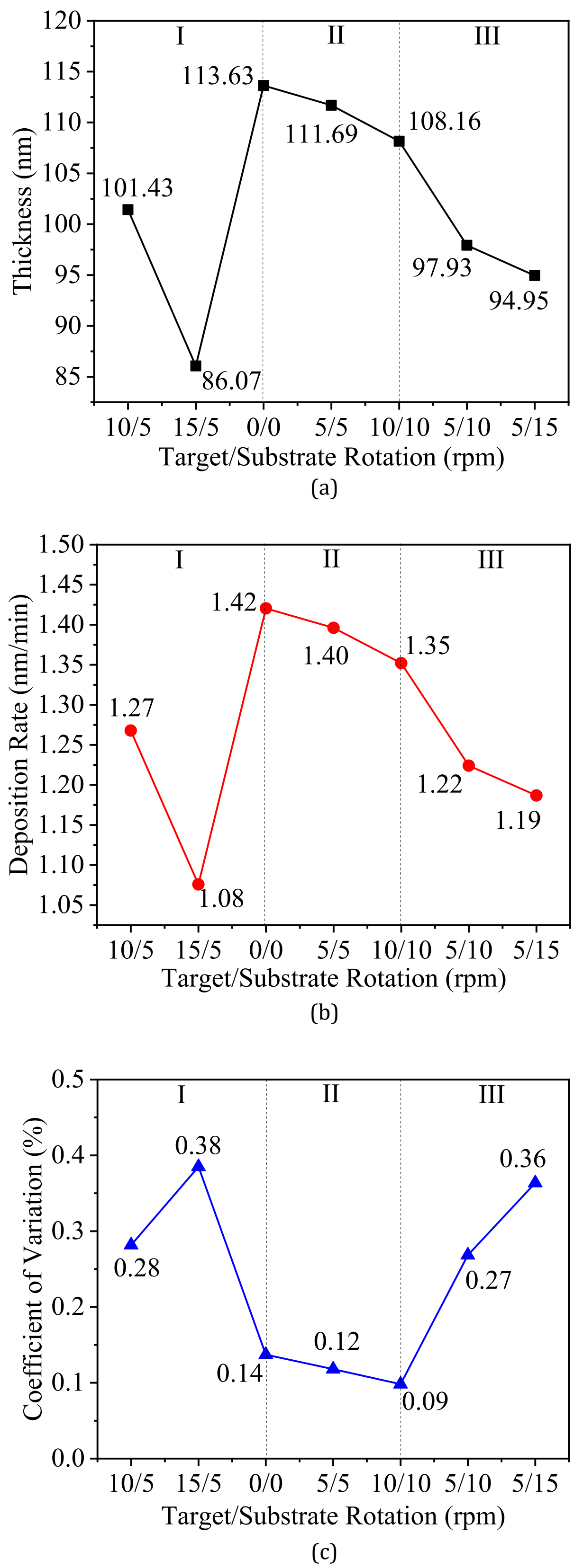


Figure 2. (a) Film thickness, (b) deposition rate, and (c) uniformity of film thickness.

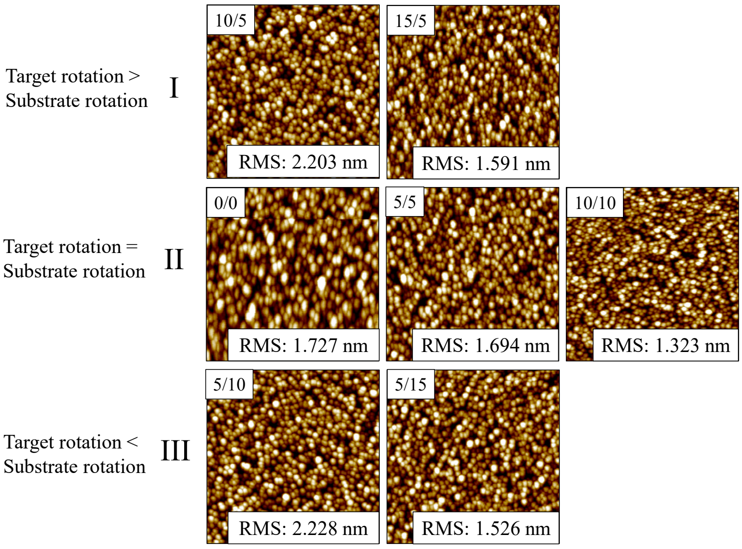
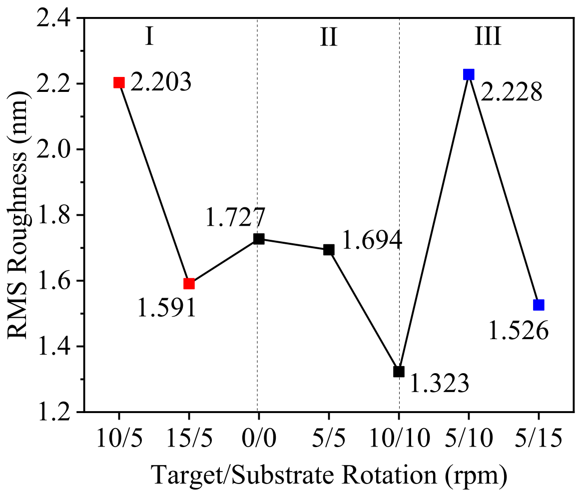
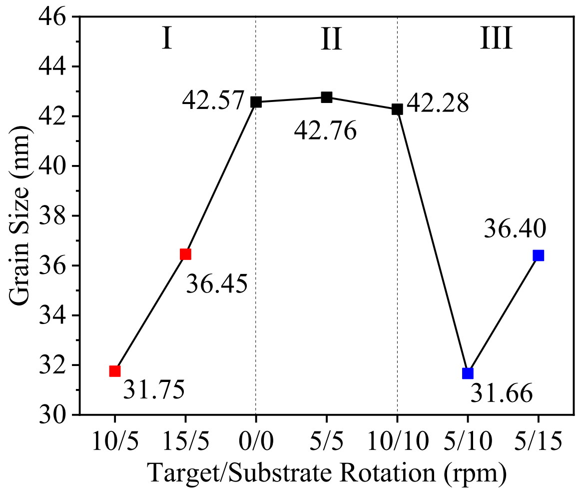


Figure 3. AFM results for various target/substrate rotation speeds.



(a)



(b)

Figure 4. (a) RMS roughness and (b) grain size of the deposited AlN using various target/substrate rotations.

Figure **5**(b) depicts the full width at half maximum (FWHM) numbers through different rotation conditions, where the lowest FWHM is achieved at 10/10 rpm, indicating superior crystal quality. A lower FWHM corresponds to reduced lattice distortion, meaning fewer defects and a more ordered atomic arrangement [25].

Figure **5**(c) further supports these findings by illustrating strain and dislocation density trends. The lowest strain occurs at 10/10 rpm, suggesting optimal stress relaxation, likely due to a more balanced adatom diffusion and deposition rate. Similarly, dislocation density follows the same trend, with the lowest values at 10/10 rpm, signifying reduced defect formation. However, strain and dislocation density increase for conditions such as 10/5, 15/5, 5/10, and 5/15 rpm. This suggests that excessive or imbalanced rotation disrupts uniform adatom distribution, introducing more structural defects rather than improving film quality [24]. The strain and dislocation density are calculated using Scherrer's formula, as shown in Equations (3), (4), and (5).

$$Strain = \frac{\beta}{4 \tan \theta} \quad (3)$$

$$Dislocation\ density = \frac{1}{D^2} \quad (4)$$

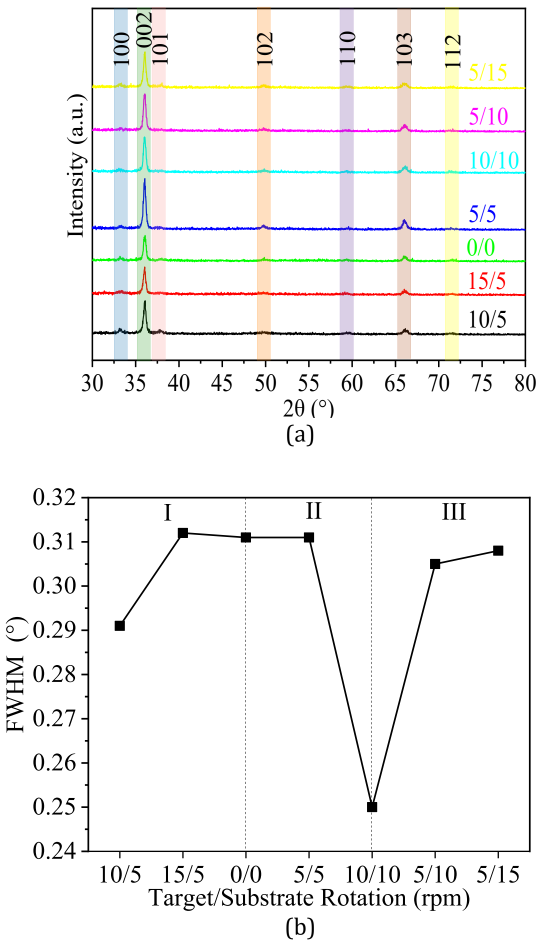
$$D = \frac{k\lambda}{\beta cos\theta} \quad (5)$$

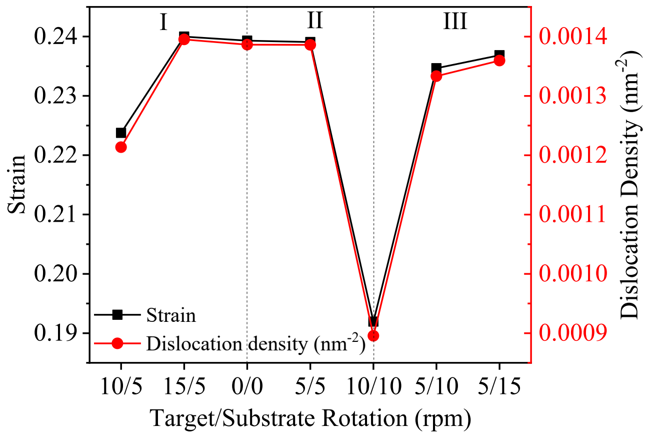
where β is the FWHM peak, θ is the angle of diffraction, D is the crystallite size, k is the Scherrer constant (0.94), and λ is wavelength for x-ray used [26], [27].

Based on the characterization results, the correlation of target and substrate rotation on the AlN thin film properties is shown in
Figure **6**. The mechanism can be described as follows: In Region I, where the target rotates faster than the substrate, a higher sputtering rate is achieved, but the deposition becomes non-uniform due to plasma density concentrating in certain areas, leading to an uneven atomic flux. As a result, the film exhibits a higher FWHM due to irregular atomic arrangement, increased strain and dislocation density caused by stress accumulation from uneven material distribution, and smaller grain size with a rougher surface due to inconsistent film growth.

In Region II, where both the target and substrate rotate at the same speed, the material distribution is more uniform, leading to optimal film growth. Consequently, a lower FWHM is achieved, indicating better crystal alignment, while strain and dislocation density are reduced, minimizing film defects. This condition also results in the best film thickness uniformity, making it the most favorable for deposition.

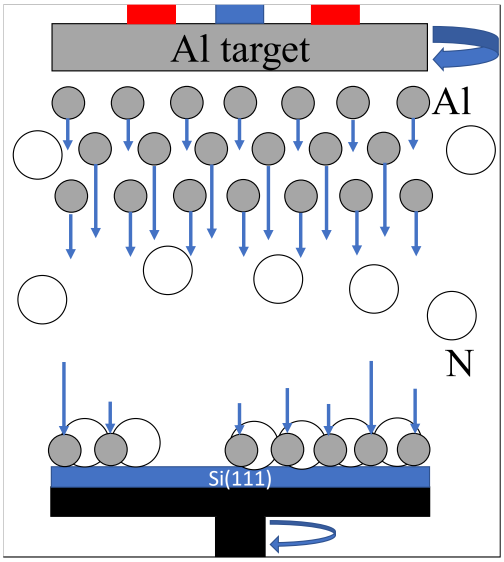
In Region III, where the substrate rotates faster than the target, excessive atomic movement disrupts controlled film growth, creating an inhomogeneous atomic flux and reducing adatom diffusion effectiveness. This leads to increased FWHM, higher strain and dislocation density due to non-uniform stress distribution, and smaller grain size with a rougher surface. The conditions in Region III closely resemble those in Region I, as both exhibit unbalanced rotation, leading to non-uniform deposition and compromised film properties.



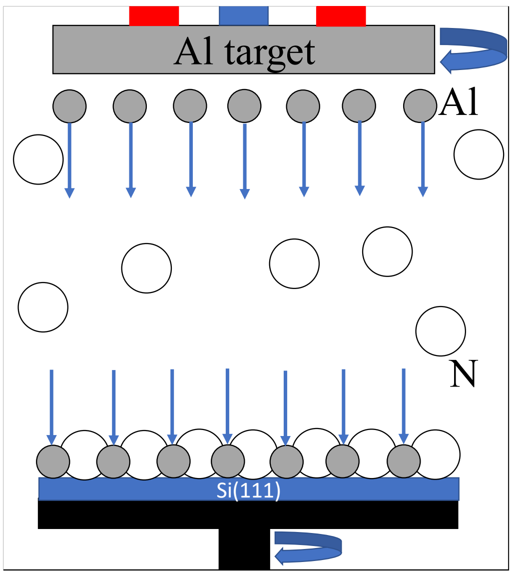


(c)

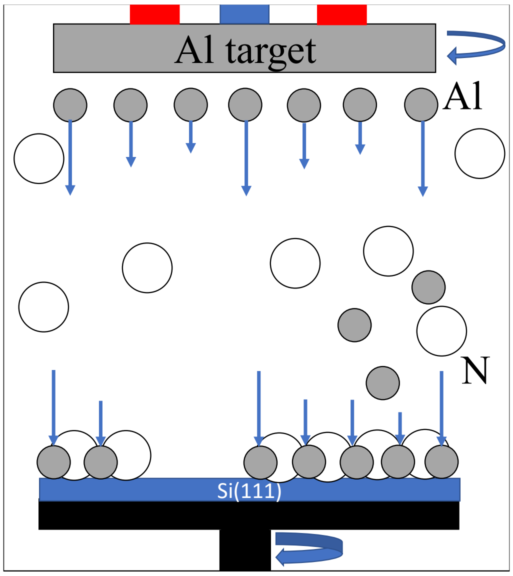
Figure 5. (a) XRD pattern of several target/substrate rotation speeds, (b) FWHM, and (c) strain and dislocation analysis.



(a)



(b)



(c)

Figure 6. Illustration of AlN thin film deposition influenced by target/substrate rotation speed in (a) Region I, (b) Region II, and (c) Region III.

4. CONCLUSION

This study investigates the effect of target/substrate rotation on AlN thin film deposition using a 12-inch RF magnetron sputtering system to optimize conditions for larger Al target sizes. Various rotation combinations (10/5, 15/5, 0/0, 5/5, 10/10, 5/10, and 5/15 rpm) are examined to assess their impact on film uniformity, surface topology, and structural properties. The results indicate that a balanced rotation speed of 10/10 rpm yields the most uniform film thickness with minimal variation, while unbalanced or lower rotation speeds result in greater thickness deviations and reduced uniformity. Topological analysis reveals that increasing both target and substrate rotation enhances surface smoothness and promotes larger grain formation. Structural characterization further demonstrates that unbalanced rotation conditions increase FWHM, strain, and dislocation density, whereas the balanced 10/10 rpm setting produces superior film quality with lower FWHM, strain, and dislocation density. Based on these findings, a 10/10 rpm rotation speed is recommended for AlN thin film deposition with a 12-inch target, ensuring optimal film properties and scalability for larger wafer applications.

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AUTHOR CONTRIBUTIONS

Natasya Salsabiila: Experiment and data collection, Writing- Initial Draft Preparation; Nafarizal Nayan: Conceptualization, Validation, Guidance; Zulkifli Azman: Writing- Editing, Nur Aqilah Saidon: Writing- Editing; Ahmad Shuhaimi Abu Bakar: Writing- Editing; Mohd Rofei Mat Husin: Writing- Editing; Mohd Yazid Ahmad: Equipment set-up; Jibril Alhaji Yabagi: Writing- Editing; Fery Adriyanto: Writing- Editing.

CONFLICTS OF INTEREST

The manuscript has not been published elsewhere and is not under consideration by other journals. All authors have approved the review, agree with its submission, and declare no conflict of interest in the manuscript.

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