Thickening-dependent optical properties of aluminum nitride films for mid-infrared wavelengths

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We present a comparative study of optical properties of aluminum nitride (AlN) thin films with different thicknesses. The films with thicknesses ranging from 66 nm to 303 nm were deposited by reactive sputtering and plasma enhanced atomic layer deposition (PEALD). Permittivity was extracted from an ellipsometry and Fourier-transform infrared (FTIR) spectroscopy reflection measurements. Our particular focus is on the influence of the deposition method and film thickness on the AlN dielectric function. Here we show that both PEALD-deposited and sputtered AlN films exhibit a monotonic dependence of negative permittivity on their thickness for vast mid-IR wavelengths including the Reststrahlen band around 11.5 – 15 µm (∼870 – 667 cm⁻¹). By structural analysis it was shown that PEALD-deposited layers contain a lower amount of oxygen and have smoother surfaces than deposited by the sputtering technique. On the other hand, sputtered films have higher densities and crystallinity, which results in the higher background permittivity (εₑ). In FTIR spectra of the PEALD-deposited layers, two specific features are observed which can be explained by higher concentration of nitrogen due to nitrogen-rich plasma in the ALD process. Such peculiarities of the optical properties of AlN films should be taken into account in potential applications of this material for metamaterials and nanostructured systems.

### I. INTRODUCTION

Currently, mid-infrared (IR) photonics that operate in the wavelength region of 2.0 – 20.0 µm (5000 – 500 cm⁻¹) has attracted great interests due to the large number of possible applications, such as chemical and biological sensing,¹⁻³ optical free-space communications,⁴ invisible-fence alarm systems,⁵ passive radiative cooling,⁶,⁷ light detection and ranging (LIDAR) systems⁸,⁹ and so on. Up to present, a wide variety of materials has been studied for mid-IR wavelengths, such as transparent dielectrics¹⁰,¹¹ phononic materials.¹² Among various mid-IR materials, one of a particular interest is aluminum nitride (AlN). Its optical properties vary from transparent dielectric to phononic material with its permittivity changing from positive to negative in the mid-IR wavelength around 11 µm (∼909 cm⁻¹).¹³ AlN is a III–V semiconductor with a wide direct band gap of 6.2 eV, good thermal conductivity, mechanical strength, decomposition temperature and chemical inertness.¹⁴ Due to those properties AlN has been used for a wide variety of applications in microelectronic and optoelectronic devices,¹⁵ such as light emitting diodes (LED),¹⁶ resonators,¹⁷ microwave filters,¹⁸ dye-sensitized solar cells,¹⁹ and so forth. AlN is transparent from visible to mid-IR wavelengths and can be considered as a low-loss material up to 10 µm²⁰,²¹ (∼1000 cm⁻¹).²² Above 11 µm (∼909 cm⁻¹) to 15 µm (∼667 cm⁻¹), AlN exhibits negative permittivity due to its phonon resonance in the region called the Reststrahlen band, which can be exploited for mid-IR photonics in order to manipulate infrared light.¹² Another interesting optical property of AlN within the wavelength region is the epsilon-near-zero (ENZ) regime²³ near the longitudinal optical (LO) phonon frequency, where the permittivity of AlN becomes close to zero. The real part of the constant vanishes around 11.3 µm (∼885 cm⁻¹), while the imaginary part is relatively small.¹²,¹³,²⁴–²⁷ Recently, various ENZ materials have drawn attention due to intriguing optical effects associated with vanishing permittivity²⁸ and studied for sensing,²⁹ enhanced fluorescence emission,³⁰ enhanced transmission through subwavelength apertures,³¹ strong subwavelength field enhancement,³² and engineering the frequency response of optical antennas.³³–³⁵

There are various methods of AlN thin films deposition including carbothermal nitridation of Al₂O₃ and subsequent sintering,³⁶,³⁷ molecular beam epitaxy (MBE),³⁹ sputtering,¹³,⁴⁰ and atomic layer deposition (ALD).⁴¹ ALD is a well-known technique that allows to obtain high-quality films with precise thickness control.⁴² ALD deposition has been successfully applied for the fabrication of different high aspect ratio nanostructures with various materials, such as Al₂O₃, TiO₂,⁴³ Al-doped ZnO trenches,⁴⁴–⁴⁶ pillars,⁴⁷ and tubes,⁴⁸ TiN trenches and tubes,⁴⁹ multi-compound coaxial tubes.⁵¹ However, conventional thermal ALD requires temperatures higher than 400 °C that above the trimethylaluminum (TMA) decomposition temperature. This typically leads to higher carbon and hydrogen presence in the deposited films and lower quality of the coatings. The use of plasma enhanced atomic layer deposition (PEALD) allows much better quality, since it enables the deposition at lower temperatures.⁵²,⁵³ However, optical properties and ENZ behaviour for mid-IR wavelengths have been mainly studied for AlN deposited by sputtering films¹³,²⁴–²⁶ or MBE.⁵⁷ In addition, there are very few studies whose optical properties were retrieved for films of different

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thicknesses. However, this was performed mainly by ellipsometry and is limited by the near-infrared wavelengths. Extension of such analysis for longer wavelengths, up to mid-IR wavelengths where its permittivity turns from positive to negative into Reststrahlen band, is urgently required due to the advent of mid-IR absorption sensing.

Hence, in this paper we report on the mid-IR optical properties of AlN deposited by PEALD with NH₃ and N₂ plasma, and reactive sputtering. The AlN film thickness measured independently by spectroscopic ellipsometry and X-ray reflectivity (XRR) ranges from 66 nm to 303 nm. Optical characterization of the films was carried out using an ellipsometer and Fourier-transform infrared (FTIR) spectrometer covering the vast wavelength interval from 210 nm to 20.0 µm (∼47619 – 500 cm⁻¹). From the reflectance data we extracted a dielectric function of each film and revealed that there is a monotonic thickness dependence on AlN’s real part of permittivity function of each film and revealed that there is a monotonic dependence by PEALD while sputtered AlN films show saturation of such dependence. In addition, structural properties of the coatings were characterized by (XRR), X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS) and atomic force microscopy (AFM) in order to understand how certain composite properties affect dielectric function.

II. ALN FILM DEPOSITION

We fabricated two sets of AlN thin film samples by different techniques. The first set of samples was made by PEALD using NH₃-based plasma. Thicknesses of samples as given by ellipsometry and XRR are: 66, 103, 128, 203, and 298 nm. The second set was created by reactive sputtering aiming thicknesses as close as possible to those of the first set. We ended with thicknesses 66, 98, 131, 170, 202, and 303 nm. Additionally to test plasma dependence of PEALD samples we fabricated a sample with thickness of 98 nm by N₂-plasma enhanced ALD. All films were deposited on 350 µm thick double-side polished Si (100) substrates.

A. PEALD deposition

The PEALD deposition was carried out in a commercial hot-wall reactor (R200 Advanced, Picosun) equipped with the remote plasma source. To prevent oxidation and presence of moisture, the tool has a load-lock used for delivering the substrates into the reactor chamber. The precursors used for AlN deposition were TMA supplied by Stream Chemicals and either NH₃ or N₂ enhanced by plasma. The deposition temperature was set at 350 °C and plasma power to 3000 W for all of the PEALD runs. The recipe used in this work is presented in Table I. The deposition rate is measured to be 0.137 and 0.056 nm/cycle for NH₃ and N₂ processes, respectively.

<table>
<thead>
<tr>
<th>Sample thickness (nm)</th>
<th>Number of cycles</th>
<th>Precursor Carrier gas flow (sccm)</th>
<th>Pulse time (s)</th>
<th>Purge (s)</th>
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<tr>
<td>66</td>
<td>568</td>
<td>TMA 100</td>
<td>0.1</td>
<td>8.0</td>
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<tr>
<td>103</td>
<td>852</td>
<td>NH₃ 150</td>
<td>5.0</td>
<td>30.0</td>
</tr>
<tr>
<td>128</td>
<td>1136</td>
<td>NH₃ 150</td>
<td>5.0</td>
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<tr>
<td>203</td>
<td>1704</td>
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<tr>
<td>298</td>
<td>2272</td>
<td>NH₃ 150</td>
<td>5.0</td>
<td>30.0</td>
</tr>
<tr>
<td>98</td>
<td>1750</td>
<td>N₂ 150</td>
<td>20.0</td>
<td>30.0</td>
</tr>
</tbody>
</table>

B. Sputtering deposition

The reactive sputtering deposition was carried out in a commercial sputter system (CMS-18 from Kurt J. Lesker Company). To prevent or reduce moisture and other impurities the tool has a load-lock used for delivering the substrates into the process chamber. During the deposition, the substrates were heated and kept at 400 °C. The deposition consisted of two stages. First, pre-sputtering of Cr with the closed substrate shutter was performed for 3 minutes in order to bind the remained water vapour and lower the base pressure inside the chamber. Second, the AlN sputtering itself was proceeded. The recipe used in this work is presented in Table II. The deposition rate is measured to be 0.06 nm/s.

<table>
<thead>
<tr>
<th>Sample thickness (nm)</th>
<th>Deposition time (s)</th>
<th>Gas 50% N₂ in Ar</th>
<th>Pressure (mTorr)</th>
<th>Target Power (W)</th>
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<tr>
<td>67</td>
<td>990</td>
<td>1 Al 300</td>
<td></td>
<td></td>
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<tr>
<td>98</td>
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<td></td>
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<tr>
<td>131</td>
<td>2180</td>
<td>1 Al 300</td>
<td></td>
<td></td>
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<tr>
<td>170</td>
<td>3200</td>
<td>1 Al 300</td>
<td></td>
<td></td>
</tr>
<tr>
<td>202</td>
<td>3600</td>
<td>1 Al 300</td>
<td></td>
<td></td>
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<tr>
<td>303</td>
<td>5000</td>
<td>1 Al 300</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

III. STRUCTURAL CHARACTERIZATION

A. Elemental analysis by XPS

The chemical composition of the films was investigated by X-ray photoelectron spectroscopy using an instrument (K-Alpha by Thermo Fisher Scientific) equipped with the Al Kα X-ray source with photon energy 1486.6 eV. The full XPS survey spectra and high resolution scans of Al −2p, N −1s, C −1s, and O −1s signals were analysed. It shows (see Table III) that the films made by ALD tend to have more preferable stoichiometry (an Al/N ratio close to 1) and less impuri-
ties compared to sputtered films. Oxygen contamination with concentration more than 11% is observed in all films. This phenomena has been reported previously. This occurs as a result of the high reactivity of aluminum and oxygen, which origin includes leaks, wall outgassing, insufficient chamber passivation, and the traces that enter through the load-lock. Minor carbon impurities, less than 1 at.% was observed in all prepared samples, except the film prepared by PEALD using pure N₂ plasma. In this particular case, the carbon concentration was very pronounced (8.3 at.%) most probably appeared due to insufficient reaction of N₂ plasma species with TMA.

| TABLE III. XPS results for both PEALD and reactive sputtering AlN film samples. |
|------------------------------|----|----|----|----|----|
| Sample thickness (nm) | Al (at.%) | N (at.%) | O (at.%) | C (at.%) | Al/N |
| PEALD NH₃ | 66 | 47.5 | 40.8 | 11.6 | 0.1 | 1.17 |
| | 103 | 48.1 | 40.6 | 11.2 | 0.2 | 1.18 |
| | 128 | 47.8 | 41.1 | 11.0 | 0.1 | 1.16 |
| | 203 | 47.7 | 41.0 | 11.2 | 0.1 | 1.16 |
| | 298 | 47.6 | 41.1 | 11.2 | 0.1 | 1.16 |
| PEALD N₂ | 98 | 41.7 | 36.3 | 13.5 | 8.3 | 1.15 |
| Sputtering | 67 | 48.6 | 39.0 | 11.5 | 0.7 | 1.25 |
| | 98 | 47.7 | 35.9 | 15.4 | 0.6 | 1.33 |
| | 131 | 48.6 | 37.4 | 13.2 | 0.6 | 1.30 |
| | 170 | 46.6 | 37.3 | 15.0 | 1.0 | 1.25 |
| | 202 | 48.3 | 36.1 | 14.9 | 0.6 | 1.34 |
| | 303 | 46.5 | 31.1 | 20.9 | 1.1 | 1.49 |

B. XRR analysis

X-ray reflectivity measurements were performed with a Rigaku SmartLab 3kW diffractometer equipped with Cu Kα X-ray source. The incoming beam was of small divergence and adequately monochromated by carefully selecting the optical scheme - a parabolic multilayer mirror, Ge(220) double-bounce monochromator and slits. Density, thickness, and surface roughness were obtained by fitting the measured XRR data to a theoretical model using Rigaku XRD Smartlab reflectivity analysis software. The implemented model contains the silicon substrate, native silicon oxide layer, and deposited AlN film with a thin surface layer of lower density to compensate for moisture and oxidation effect. XRR results reveal that the sputtered AlN films have significantly higher densities (supplementary material at [URL will be inserted by AIP Publishing]) compared to ALD films. The measured density of about 3.2 g/cm³ is the same as reported for the fully crystalline AlN. On the contrary, the ALD samples have density values close to values reported for amorphous or polycrystalline ALD-deposited AlN films (2.5–2.8 g/cm³). Analysis of the roughness showed that ALD films were smoother compared to sputtered films. The slightly higher average roughness of the sputtered films could be attributed to the more precise, self-limiting deposition protocol of ALD. Also, for both ALD and sputtered films the average roughness increases a bit with the thickness. These results are in a good agreement with reported in literature. In addition, the roughness and thickness of thin films were independently estimated by AFM and ellipsometry measurements, respectively.

C. XRD analysis

To gain further information on the structural properties of the AlN thin films, X-ray diffraction measurements were performed using the same equipment as in the case of XRR. θ-2θ scans were acquired in a parallel beam geometry implementing a parabolic multilayer mirror and using the incident and receiving slits of 0.5 mm and a set of Soller slits of 5° to minimize the beam divergence. The scan was conducted at the 20 – 90° angle range of 2θ. For both ALD and sputtered films, the peaks around 36° and 38° were observed, which attributed to the (002) and (101) crystalline AlN orientation, respectively. Since the peak at 36° is more pronounced compared to 38° for all the deposited films, the growth favors the (002) orientation instead of the (101). For the sputtered films both peaks are more pronounced due to higher crystallinity level of the structure, which is in agreement with the XRR measurements. The Lorentzian fit through the measured peaks allowed estimating the average grain size by the Scherrer equation:

$$D = \frac{K\lambda}{\beta \cos(\theta)}$$

Here, K is the Scherrer factor, λ is the wavelength of Cu Kα.
radiation, $\theta$ is a Bragg angle and $\beta$ is the full-width at half-maximum (FWHM) of the observed peak with instrumental correction ($0.13^\circ$). The results presented in Fig. 1 demonstrate a monotonically increasing nonlinear dependence of the average crystallite size $D$ with the film thickness. Hence, increasing the thickness leads to the growth of the crystallinity of the thin films, which is indicated by rising and narrowing of the diffraction peak. Furthermore, it is obvious that the grain size of a sputtered layer is higher in comparison with the ALD sample (for PEALD distinct peaks appear only from 200 nm thickness). The average grain size was also independently estimated by AFM measurements.

D. AFM analysis

The accuracy of surface roughness evaluated by XRR analysis was additionally verified by atomic force microscopy (AFM Dimension Icon-PT by Bruker AXS) operated in the tapping mode. The root-mean-square (RMS) surface roughness was determined for each film as shown in supplementary material at [URL will be inserted by AIP Publishing]. Supporting the XRR analysis, it was observed that roughness of the samples increases with the thickness. The AFM images of the AlN film of 100 nm thickness made by both PEALD (with NH$_3$ and N$_2$ plasma) and reactive sputtering are shown in Fig. 2. See supplementary material at [URL will be inserted by AIP Publishing] for images with other thicknesses. Moreover, the grain size estimation was performed using the watershed algorithm implemented in the NanoScope Analysis 1.7 software, where only separated grains were considered due to their statistical significance. As for the XRD analysis, an increase in the grain size with the film thickness was observed.

IV. OPTICAL CHARACTERIZATION

A. Spectroscopic ellipsometry for visible and near-infrared wavelengths

The film thickness and permittivity of the AlN film samples were measured using an ellipsometer (VASE by J. A. Woollam Co). The measurements were performed in a spectral range of 210 – 1690 nm ($\sim$47619 – 5917 cm$^{-1}$). $\Psi$ and $\Delta$ ellipsometry parameters were measured at three angles of incidence ($55^\circ$, $60^\circ$ and $65^\circ$) and the corresponding experimental dielectric constants were extracted by the Cauchy-Urbach model.$^{61-64}$ Fitted example, all obtained coefficients and the real and imaginary parts of dielectric functions ($\varepsilon_1$ and $\varepsilon_2$), are presented in supplementary materials [URL will be inserted by AIP Publishing]. From the data, we can observe that the background permittivity ($\varepsilon_\infty$) increases with the growing thickness. Moreover, the value for the films made by reactive sputtering is higher than those made by PEALD. According to the XRR and XRD data, sputtered films have higher densities and higher crystallinity in comparison with ALD films. The improvement of crystallinity leads to increasing of $\varepsilon_\infty$ and therefore overall dielectric constants as well.

B. FTIR measurement for mid-infrared wavelengths and fitting

Free-space reflection measurements in the mid-infrared range were conducted by the FTIR spectrometer (VERTEX 70, Bruker).$^{44,47,65}$ A series of measurements were performed with the unpolarized incident light in the wavelength range of $\lambda = 2.0 – 20.0$ $\mu$m (5000 - 500 cm$^{-1}$) with resolution of 4 cm$^{-1}$. The measured reflectance spectra in supplementary material at [URL will be inserted by AIP Publishing] are the average of five different points on each sample and each measurement is the average of 32 scans. All measurements were performed at the incidence angle of $12^\circ$. Each reflectance spectrum was normalized by that from an aluminum mirror. As an example, we show the measured reflection spectra and fitted reflection of sputtered AlN films in Fig. 3.

The FTIR reflectance spectra of the samples exhibit various vibrational modes, which can be classified according to their origin as AlN, Si/SiO$_2$ and carbonaceous/aqueous ones. The peaks around 4.23 ($\sim$2364 cm$^{-1}$) and 14.95 $\mu$m ($\sim$669 cm$^{-1}$) presented in most of samples can be assigned

FIG. 2. AFM and images ($1\,\mu$m scale) of samples made by (a) reactive sputtering, (b) PEALD with N$_2$- and (c) NH$_3$-plasmas, respectively.

FIG. 3. FTIR experimental and fitted reflection for sputtered AlN films with various thicknesses.
FIG. 4. Real (a,b) and imaginary (c,d) permittivity of AlN films deposited by PEALD NH$_3$, N$_2$ plasmas and reactive sputtering, respectively.

to CO$_2$ absorption due to the deviating CO$_2$ levels in the atmosphere. In some cases, the pronounced peak at 14.95 µm of CO$_2$ is present in reflection spectra. Therefore, we did not fit simulated reflectance for this particular peak in retrieving the permittivities of AlN films. The features around 2.7 µm (∼3704 cm$^{-1}$) and very broad in the 5.2 – 7.9 µm (∼1923 – 1266 cm$^{-1}$) range are attributed to water absorption. Moreover, in the second broad band can be also contributions from the asymmetric and symmetric bending modes, respectively, of methyl, methyne, and methylene groups, which are common impurities in thin films deposited with TMA-based processes. The relatively strong features around 16.5 µm (∼606 cm$^{-1}$) and less intense around 10.3 (∼971 cm$^{-1}$) and 11 µm (∼909 cm$^{-1}$) are assigned to the Si modes. The band around 12 µm (∼833 cm$^{-1}$) is assigned to the Si—N bond, which is possibly created due to the diffusion of Si atoms into the AlN matrix. The other feature observed around 13.5 µm (∼741 cm$^{-1}$) arise from the native oxides of the substrates. In addition, it is possible that longitudinal optical (LO) phonon mode of Al-N and stretching Al-O mode contribute to the features around 13.5 and 11.3 µm (∼885 cm$^{-1}$), respectively. However, it is hard to distinguish those from the Si and SiO$_2$ modes.

The band around 15 µm (∼667 cm$^{-1}$) observed for all samples could be assigned to the transverse optical (TO) phonon mode of Al-N. In addition, in the data obtained for PEALD with NH$_3$ plasma two new resonances are clearly seen around 3.2 (∼3125 cm$^{-1}$) and 4.7 µm (∼2128 cm$^{-1}$). The band at 3.2 µm is attributed to NH stretching in Al–NH$_2$ and the band at 4.7 µm is assigned to Al–N$_2$ bonding. The feature at 4.7 µm is also seen for PEALD with N$_2$ plasma, whereas for the sputtered samples these low-wavelength resonances are absent.

C. Optical properties/permittivities

The measured FTIR reflection and fitted reflection spectra by using the RefFit software are shown in Fig. 3 and supplementary material at [URL will be inserted by AIP Publishing]. The entire procedure of permittivity retrieval is given in supplementary material at [URL will be inserted by AIP Publishing]. First, we retrieved the permittivity of a 350 µm double side polished Si substrate from the free-space reflection. The permittivity of Si substrate was found by fitting the simulated reflection spectra to the measured reflection, assuming that the permittivity of Si follows the Lorentz model with seven Lorentzian terms (supplementary material at [URL will be inserted by AIP Publishing]). The Si substrate’s permitt-
complex permittivity. The zero-crossing wavelength for \( \epsilon_1 \) is around 11.25 \( \mu \text{m} \) (~888 cm\(^{-1}\)) and slightly red-shifted with the increase of the thickness for the both sputtered and PEALD-deposited films with NH\(_3\) and N\(_2\) plasma, respectively. That point is associated with the LO phonon frequency for the undamped system.\(^{82}\) In the concordance with the ellipsometry data that shows an increase of \( \epsilon_\infty \) with growing of the sample thickness, the peak intensity of the real part of permittivity around 15.0 \( \mu \text{m} \) also rises with the growing sample thickness, as shown in Fig. 5(a). From the figure, we can observe that the change in negative permittivity peak becomes larger as the film thickness increases for the both sputtered and PEALD-deposited films. This trend swaps from monotonic increase to decrease below 11.2 \( \mu \text{m} \) (~893 cm\(^{-1}\)) and also above 16.1 \( \mu \text{m} \) (~621 cm\(^{-1}\)). For the imaginary part at the same wavelength as shown in Fig. 5(b), we also see the trend where growing sample thickness reduces the value of imaginary part of permittivity. This is due to the fact that the scattering constant \( \gamma \), obtained from fitting, decreases with increasing film thickness that results in more crystallinity of the layers according to the XRD and AFM analysis. The more crystalline is the layer, the less is the scattering constant. In addition, this trend is also shown by decrease of the imaginary part of permittivity, associated with losses.

In summary, we have investigated structural and optical properties of AlN films with different thicknesses ranging from 66 nm to 303 nm fabricated by PEALD with NH\(_3\) and N\(_2\) plasma, as well as by reactive sputtering. These films are characterized by ellipsometry, FTIR, XRR, XRD, XPS and AFM to conduct elemental analysis and compare composite and optical properties and their influence on dielectric functions of AlN on mid-IR wavelengths. The PEALD-deposited films are less contaminated with oxygen and have smoother surfaces in comparison with the sputtered films. According to the XRR, XRD and AFM data, the sputtered films, in contrary, have higher densities and higher crystallinity than the ALD films. The increase of the film crystallinity leads to the growth in permittivities, which is shown as the rise of \( \epsilon_\infty \) value and intensity of permittivity peak due to decrease of the scattering constant. Moreover, higher concentration of N obtained in the PEALD films results in higher probability of creation of Al–NH\(_3\) and Al–N\(_2\) bonding. The corresponding peaks are spotted in the FTIR spectra. We observe a distinct almost monotonic dependence of the dielectric func-

### Table IV. Fitted Lorentz parameters of AlN films.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sample thickness (nm)</th>
<th>( \epsilon_\infty )</th>
<th>( \omega_{TO} )</th>
<th>( \gamma_1 )</th>
<th>( \omega_{LO} )</th>
<th>( \gamma_2 )</th>
<th>( \omega_3 )</th>
<th>( \gamma_3 )</th>
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<tbody>
<tr>
<td>PEALD NH(_3)</td>
<td>66</td>
<td>3.68</td>
<td>649</td>
<td>31.7</td>
<td>2077</td>
<td>119</td>
<td>3204</td>
<td>332</td>
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</tbody>
</table>

FIG. 5. The dependence of the change in (a) the real and (b) imaginary part of peak permittivity around 15.1 \( \mu \text{m} \) in wavelength with increasing film thickness deposited by PEALD with NH\(_3\) and sputtering.

### V. CONCLUSION

D. Structural and optical properties

Figure 4 shows the retrieved real and imaginary parts of complex permittivity. The zero-crossing wavelength for \( \epsilon_1 \) is around 11.25 \( \mu \text{m} \) (~888 cm\(^{-1}\)) and slightly red-shifted with the increase of the thickness for the both sputtered and PEALD-deposited films with NH\(_3\) and N\(_2\) plasma, respectively. That point is associated with the LO phonon fre-
tion of the films on their thickness for both sputtered and PEALD-deposited AlN films. This trend was observed for wide mid-IR wavelengths beyond 2.0 µm (≈5,000 cm⁻¹) that we characterized including the Reststrahlen band from 11.5 – 15 µm (≈870 – 667 cm⁻¹). The slope of such dependence is defined by the fabrication routine, and in our case is higher for sputtered samples. This fact as well as process-dependent films parameters must be taken into account while designing nanostructured elements with phononic and ENZ features for mid-infrared photonics.

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Independent Research Fund Denmark (DFF) (Research Project 2, 8022-00387B), Denmark.

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DATA AVAILABILITY

The data that support the findings of this study are available within the article and its supplementary material. The data are also available from the corresponding author upon reasonable request.

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