

## Review

# Nanoindentation-Derived Mechanical Properties of Cubic III-Nitrides on MgO(001)-Based Templates: c-GaN, c-In<sub>x</sub>Ga<sub>1-x</sub>N, and c-InN

Esteban Cruz-Hernández , Edgar López-Luna  and Miguel A. Vidal \*

Coordinación para la Innovación y la Aplicación de la Ciencia y la Tecnología (CIACYT), Universidad Autónoma de San Luis Potosí (UASLP), San Luis Potosí 78210, Mexico

\* Correspondence: miguel.vidal@uaslp.mx

## Abstract

Mechanical reliability is an essential prerequisite for III-nitride thin films throughout device fabrication and processing. However, the availability of nanoindentation data for metastable cubic phases remains limited, making cross-study comparisons particularly challenging. In this context, the present work offers a unified compilation of hardness ( $H$ ) and Young's modulus ( $E$ ) values derived from nanoindentation of cubic epilayers grown by plasma-assisted molecular beam epitaxy (MBE) on MgO(001)-based templates, encompassing c-GaN, c-In<sub>x</sub>Ga<sub>1-x</sub>N alloys ( $x = 0.26\text{--}0.72$ ), and c-InN. The three underlying studies utilize consistent metrological approaches: Berkovich indentation with Oliver–Pharr analysis, polished surfaces exhibiting low root-mean-square (RMS) roughness, and a shared MgO/c-GaN-templated stack. This methodological alignment enables a composition-aware comparison across the c-GaN/c-In<sub>x</sub>Ga<sub>1-x</sub>N/c-InN series. Consolidated  $H$  and  $E$  values are examined as functions of the indium fraction,  $x$ , while their depth dependence is used to distinguish the film-dominated response from the increasing influence of the template or substrate. Additionally, a focused comparison with representative wurtzite data situates the cubic results within a broader context, while maintaining emphasis on MgO-based heteroepitaxy. Ultimately, the resulting dataset and analysis provide a practical resource for mechanically informed processing and reliability evaluation in cubic III-nitride systems.

**Keywords:** cubic III-nitrides; MgO(001); nanoindentation; hardness; Young's modulus; c-GaN; c-InGaN; c-InN

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## 1. Introduction

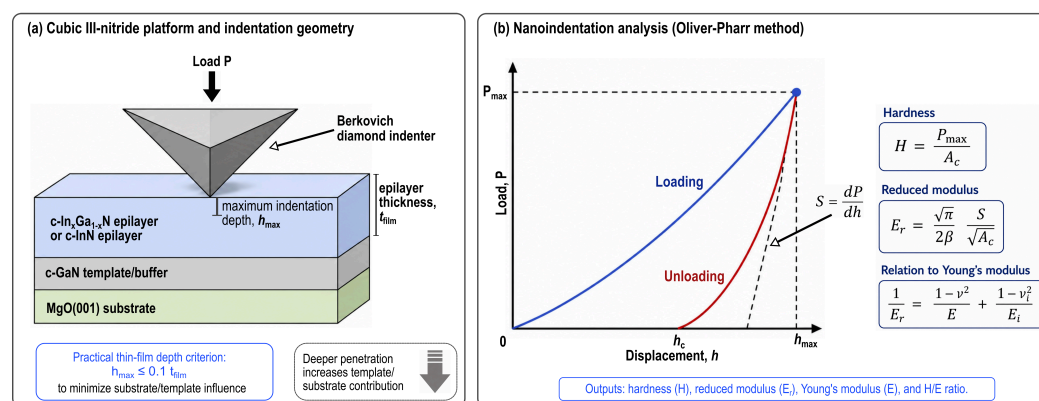
Mechanical robustness is a practical constraint that III-nitride thin films must satisfy throughout device fabrication: wafer handling, polishing, lithography, metallization, and packaging all generate localized contact stresses that can compromise structural integrity before a device ever operates. In GaN-based light-emitting diodes (LEDs), substrate and template selection are central drivers of defect concentration, thermal management, and manufacturing cost, motivating sustained efforts to grow III-nitrides on alternative platforms beyond conventional sapphire [1]. Beyond conventional LEDs, III-nitrides are also central to emerging micro-LED displays, long-wavelength InGaN emitters, GaN-on-Si power electronics, and vertical GaN device technologies [2–7]. While most devices exploit the thermodynamically stable wurtzite phase, cubic (zincblende) III-nitrides can be stabilized under non-equilibrium growth conditions, offering higher crystal symmetry, a distinct defect landscape, and compatibility with (001)-oriented cubic substrates.

Despite the significance of this topic, consolidated mechanical datasets for cubic III-nitrides remain limited. Reported nanoindentation values are often difficult to compare across studies due to variations in substrates, film thickness, surface roughness, and analysis methodologies. This review adopts MgO(001)-based cubic stacks as a unifying framework and presents a harmonized compilation of nanoindentation-derived hardness ( $H$ ) and Young's modulus ( $E$ ) for c-GaN, c-In<sub>x</sub>Ga<sub>1-x</sub>N alloys, and c-InN. The mechanical dataset is sourced from three studies by the same research group [8–10], collectively covering the complete cubic III-nitride series on MgO(001)-based templates: c-GaN [9], c-In<sub>x</sub>Ga<sub>1-x</sub>N alloys [8], and c-InN [10]. The platform context is established through key studies on phase selection, plasma-assisted growth, buffer-mediated heteroepitaxy, and InN properties [11–15]. A targeted comparison with representative wurtzite data situates the cubic dataset within the broader III-nitride mechanical landscape.

Accordingly, this article is intended as a focused review and critical analysis of an internally consistent MgO(001)-based cubic III-nitride dataset, rather than as an exhaustive survey of all mechanical-property reports on III-nitrides. The datasets were selected because they share a common MgO/c-GaN-based platform, comparable Berkovich nanoindentation methodology, Oliver–Pharr analysis, polished surfaces with low root-mean-square (RMS) roughness, and documented thickness/depth-window considerations. Here, the indium fraction ( $x$ ) serves as the compositional variable for the specific c-GaN/c-In<sub>x</sub>Ga<sub>1-x</sub>N/c-InN series considered in this review.

## 2. Cubic III-Nitrides on MgO(001): Platform Overview

MgO(001)-based cubic stacks are employed as the reference platform in this review, providing a consistent multilayer geometry for both epitaxial growth and mechanical characterization. Figure 1 presents the stack architecture: an MgO(001) substrate supports a c-GaN template, upon which c-In<sub>x</sub>Ga<sub>1-x</sub>N or c-InN epilayers are deposited. The figure also details the nanoindentation workflow, which links the measured load–displacement response to the primary outputs—hardness ( $H$ ), Young's modulus ( $E$ ), and the dimensionless ratio  $H/E$ . Additionally, it emphasizes the use of a conservative depth-window criterion (indentation depth  $\leq 10\%$  of film thickness) to minimize substrate and template effects when interpreting thin-epilayer data.



**Figure 1.** Schematic representation of the cubic III-nitride platform and nanoindentation analysis considered in this review. (a) MgO(001)/c-GaN template structure with c-In<sub>x</sub>Ga<sub>1-x</sub>N or c-InN epilayers, showing the Berkovich indentation geometry, the epilayer thickness, and the practical thin-film depth criterion used to minimize substrate/template contributions. (b) Representative load–displacement response and Oliver–Pharr analysis parameters used to extract hardness ( $H$ ), reduced modulus ( $E_r$ ), Young's modulus ( $E$ ), and the  $H/E$  ratio. Schematic not to scale.



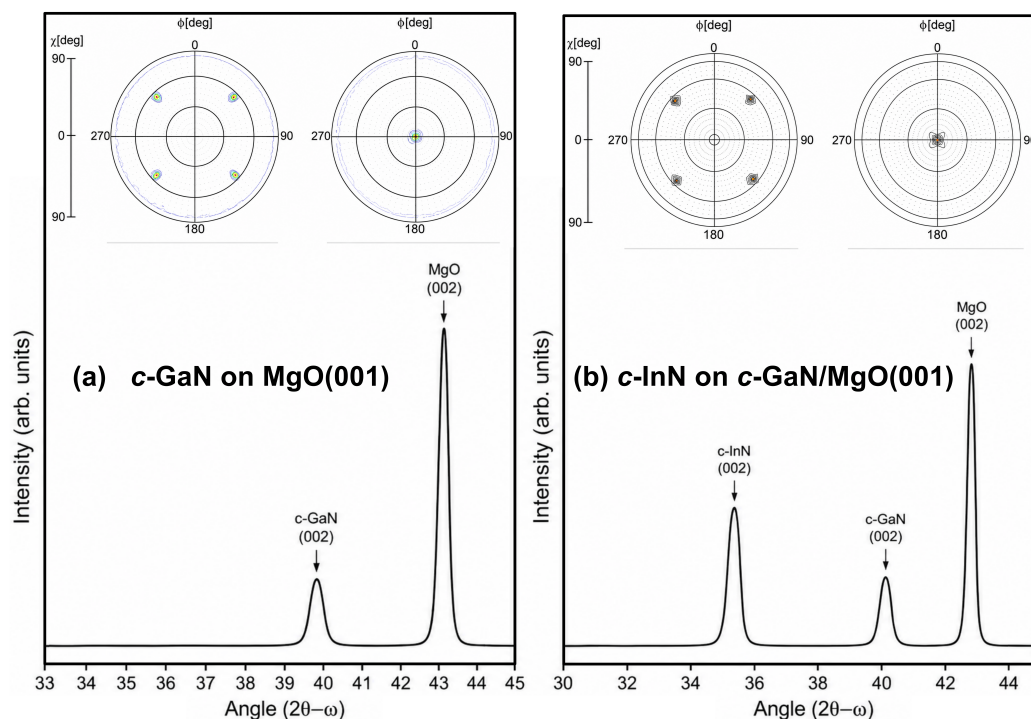
### 2.1. Rationale for Selecting the MgO(001) Platform and the Cubic Phase

Getting cubic III-nitrides to grow reliably is not straightforward. Under most conditions, GaN, InN, and their alloys naturally form the wurtzite phase because it is thermodynamically stable. The cubic phase only appears when the growth conditions are tuned carefully enough to steer nucleation and surface diffusion away from the equilibrium path. Work on GaN grown by reactive-ion molecular beam epitaxy (MBE) showed early on that both wurtzite and zincblende can be obtained from the same material system, with the outcome depending on kinetics and how the microstructure develops rather than on any fundamental preference of the atoms [12]. Growth conditions, particularly substrate temperature and nitrogen-plasma parameters, play an important role in stabilizing the cubic phase and determining the structural quality of III-nitride films [13]. In the datasets considered here, however, these parameters were optimized for each material system rather than varied systematically to assess their influence on the measured mechanical properties. Taking all of this together, plasma-assisted molecular beam epitaxy (PAMBE) is a reasonable approach for pushing cubic nitrides onto cubic substrates.

MgO works well as a substrate here because its (001) surface is cubic and supports the kind of epitaxial stacking that keeps the growing nitride film in the (001) orientation. In practice, a c-GaN layer is grown first and acts as a structural buffer between the MgO and any indium-containing epilayer deposited on top. This reduces the direct influence of MgO on both the growth and the indentation response and, importantly, provides a common underlying layer for comparing the different compositions. However, it does not completely eliminate the mechanical contribution of the template/substrate stack, particularly at larger indentation depths. The idea is not new—low-temperature AlN buffer layers are a classic example of how an intermediate layer can promote high-quality III-nitride heteroepitaxy on a lattice-mismatched substrate [14]. The MgO/c-GaN template plays an analogous role in the cubic nitride system.

From a device standpoint, MgO is not a conventional substrate for device fabrication—it is electrically insulating and mechanically challenging to process—but standard lithographic techniques are compatible with it, and ongoing work is exploring its viability as a platform for cubic nitride devices. In addition, lattice-mismatch-related defects are concentrated near the c-GaN/MgO interface, which may increase the scatter of the nanoindentation response or contribute to pop-in events when the indenter approaches this region. Thermal conductivity, defect density, cost, and how well the process scales all matter when thinking about GaN-based LEDs [1], and exploring non-standard platforms is a reasonable response to those constraints. For indium-containing layers the situation is more complex, partly because InN itself took years to characterize properly—its optical gap turned out to be narrower than originally thought when MBE-grown material became available [15], which is a good reminder that growth control and careful characterization go together.

The mechanical data compiled in this review come from stacks where the cubic fraction is high and the orientation is well-defined. Figure 2 shows the structural evidence: X-ray diffraction (XRD) and pole figures confirm cubic-phase c-GaN on MgO(001) in Figure 2a, and the same type of data establishes the cubic character of InN on the c-GaN/MgO(001) template in Figure 2b. That is the architecture the nanoindentation comparisons are built on. Thus, MgO(001) provides a useful and internally consistent epitaxial platform, but the stack is not mechanically neutral; its contribution must be controlled through conservative indentation-depth windows and careful interpretation of the depth-dependent response.



**Figure 2.** Structural evidence supporting cubic-phase growth on MgO(001)-based stacks. (a) X-ray diffraction  $2\theta$ - $\omega$  scan and pole-figure data for c-GaN grown on MgO(001), showing the c-GaN(002) and MgO(002) reflections and the corresponding cubic orientation. (b) X-ray diffraction  $2\theta$ - $\omega$  scan and pole-figure data for c-InN grown on the c-GaN/MgO(001) template, showing the c-InN(002), c-GaN(002), and MgO(002) reflections. Panels were redrawn/adapted with permission from Refs. [9,10].

## 2.2. Significance of Mechanical Properties in This System

Mechanical properties are easy to overlook when the main interest is optical or electronic performance, but the stack still has to survive everything that happens before a device is finished. Wafer handling, polishing, lithography, metallization, and packaging all put stress on the material, and thin epilayers on templated substrates are not especially forgiving. Hardness tells you how resistant a layer is to being permanently deformed by a contact load. The elastic modulus tells you how loads are shared within the multilayer and how stress moves across interfaces. Both matter for reliability, even if neither shows up directly in an electroluminescence spectrum.

For cubic epilayers on MgO(001), this is not just a general concern. The layers are thin, grown on a heterostructure that already has residual strain and mismatch-related defects, and the mechanical response reflects all of that. The c-GaN buffer on MgO provides a consistent mechanical foundation for the indium-containing layers grown on top, which is one of the reasons it makes sense to use this platform as a reference for consolidating data across compositions. A dataset built on a common underlayer is simply easier to interpret than one assembled from films grown on different substrates with different mechanical baselines.

## 3. Nanoindentation in III-Nitrides: What Is Measured and What Biases the Result

Extracting meaningful hardness and elastic modulus values from nanoindentation of III-nitride thin films requires careful control of both experimental protocol and data interpretation. The measured quantities are sensitive to substrate and template influence, surface condition, tip calibration, and analysis assumptions—factors that collectively determine whether reported values reflect intrinsic film properties or an artifact of the measurement

geometry. This section outlines the Oliver–Pharr framework used throughout the consolidated dataset, identifies the principal sources of bias relevant to thin cubic nitride epilayers, and establishes the interpretation criteria applied in this review.

### 3.1. The Oliver–Pharr Framework

The majority of III-nitride hardness and modulus values in the literature are obtained by instrumented indentation with a Berkovich diamond tip, analyzed within the Oliver–Pharr framework [16]. Hardness is defined as the ratio of peak load to projected contact area at maximum load:

$$H = \frac{P_{\max}}{A_c} = \frac{P_{\max}}{24.5h_c^2}, \quad (1)$$

where  $P_{\max}$  is the maximum applied load,  $A_c$  is the projected contact area, and  $h_c$  is the contact depth. The elastic response is characterized through the initial unloading stiffness  $S$ , which yields the reduced modulus:

$$E_r = \frac{S}{2\beta} \frac{\sqrt{\pi}}{\sqrt{A_c}}, \quad (2)$$

where  $\beta = 1.034$  for a Berkovich tip. The reduced modulus combines the elastic response of both the film and the indenter tip, and is related to the film's Young's modulus  $E$  through:

$$\frac{1}{E_r} = \frac{1 - \nu^2}{E} + \frac{1 - \nu_i^2}{E_i}, \quad (3)$$

where  $\nu$  is the Poisson ratio of the film and  $\nu_i$ ,  $E_i$  are the known elastic constants of the diamond tip ( $E_i = 1150$  GPa,  $\nu_i = 0.07$ ). The Poisson ratio values used for each material in this review are  $\nu = 0.27$  for c-GaN and  $\nu = 0.30$  for c-In<sub>x</sub>Ga<sub>1-x</sub>N and c-InN, kept consistent with the assumptions used in the source studies and summarized in Table 1. Practical guidance on instrumented indentation methodology is provided by ISO 14577-1 [17], and comprehensive discussions of tip calibration, area functions, and common methodological challenges are available in Fischer-Cripps [18].

**Table 1.** Consolidated nanoindentation-derived mechanical properties of cubic III-nitrides on MgO(001) compiled from Refs. [8–10]. RMS values correspond to polished surfaces; uncertainties are as reported.

| Material | $x$ (In) | $t$ (nm) | RMS (nm) | $H$ (GPa)      | $E$ (GPa)     | $\nu$ | Notes                                                                             |
|----------|----------|----------|----------|----------------|---------------|-------|-----------------------------------------------------------------------------------|
| c-GaN    | 0.00     | 350      | 2.3      | $22 \pm 1$     | $293 \pm 12$  | 0.27  | PAMBE on MgO(001); polished prior to indentation. [9]                             |
| c-GaN    | 0.00     | 700      | 2.5      | $22 \pm 1$     | $293 \pm 12$  | 0.27  | Thickness series discussed for substrate-effect control and pop-in events. [9]    |
| c-InGaN  | 0.26     | 450      | 2.52     | $19.6 \pm 0.9$ | $308 \pm 16$  | 0.30  | PAMBE on c-GaN (350 nm)/MgO(001). [8]                                             |
| c-InGaN  | 0.40     | 300      | 1.91     | $19.3 \pm 0.9$ | $288 \pm 14$  | 0.30  | PAMBE on c-GaN (350 nm)/MgO(001). [8]                                             |
| c-InGaN  | 0.53     | 270      | 1.14     | $19.4 \pm 0.8$ | $281 \pm 9$   | 0.30  | Lowest RMS in the series; cubic fraction minimum reported near $x \sim 0.5$ . [8] |
| c-InGaN  | 0.72     | 230      | 1.97     | $18.7 \pm 0.7$ | $293 \pm 13$  | 0.30  | High In content within cubic regime. [8]                                          |
| c-InN    | 1.00     | ~180     | 2–4      | $12.5 \pm 0.4$ | $365.6 \pm 7$ | 0.30  | PAMBE on c-GaN (350 nm)/MgO(001); cubic fraction >97%. [10]                       |

### 3.2. Principal Artifacts Affecting Thin Cubic Nitride Epilayers

Several factors can bias nanoindentation measurements in thin films and heterostructures. How much each factor matters depends on the indentation depth, the film's thickness, and the structure of the layers.

When the indentation goes deeper, the measurement starts to reflect the properties of the layers beneath the film, not just the film itself [19]. To avoid this, it is generally recommended to keep the indentation depth below 10% of the film thickness [19]. However, this limit can change depending on differences in stiffness between the film and substrate, the stress in the layers, and the overall structure. If the guideline is not followed, both  $H$  and  $E$  will show trends with depth that actually reflect the underlying layer, not the film.

If the surface roughness is high compared to the contact depth, it can make measurements of contact area and stiffness less consistent. The three studies reviewed here [8–10] all used polished surfaces with low roughness, which helped reduce this source of error.

Whether the material around the indenter piles up or sinks in depends on the ratio of hardness to elastic modulus and how the material hardens under strain. These effects change the actual contact area, which can lead to overestimating or underestimating  $H$  and  $E$ .

Rounding of the Berkovich tip and inaccuracies in area-function calibration directly affect the projected contact area ( $A_c$ ), which in turn influences both hardness and modulus measurements. Regular calibration using a fused silica reference is essential to ensure comparability across studies.

Conversion from reduced modulus ( $E_r$ ) to Young's modulus ( $E$ ) requires an assumed Poisson ratio, which varies among c-GaN, c-In<sub>x</sub>Ga<sub>1-x</sub>N, and c-InN and depends on composition. Inconsistent selection of Poisson ratio across studies introduces systematic errors that are often overlooked when comparing datasets from different sources.

Load–displacement curves in III-nitrides can show sudden displacement bursts at nearly constant load, commonly referred to as pop-in events. These events reflect the localized activation of plastic deformation and can provide information about the defect structure of the film. In the c-GaN study, pop-in events appeared in 350 nm-thick c-GaN layers at depths over 110 nm, but not in thicker 700 nm c-GaN films tested at shallower depths [9]. This pattern matches the higher defect density near the c-GaN/MgO interface, where stacking faults are common. As the film gets thicker, some defects are partially annihilated, making pop-in events less likely. No pop-in events were seen in c-InN or c-In<sub>x</sub>Ga<sub>1-x</sub>N films within the selected depth ranges used [8,10]. Because a pop-in increases the accumulated penetration depth during loading, it locally modifies the load–displacement curve and may affect the contact geometry used in the hardness analysis. However, it does not necessarily invalidate the measurement, since the elastic modulus is primarily obtained from the initial unloading stiffness. Representative hardness and modulus values were therefore extracted from stable depth intervals and multiple indentations. Pop-in events are interpreted here as signatures of defect-mediated plasticity rather than as simple measurement artifacts.

### 3.3. Comparability Across Studies: Phase, Substrate, and Protocol

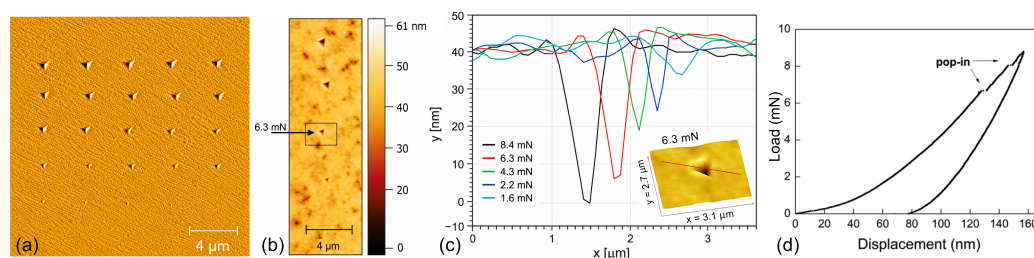
To compare nanoindentation results across III-nitride studies, several factors must be considered. The modulus is calculated from unloading stiffness and can be reported in different ways, depending on tip calibration and the Poisson ratio used. Wurtzite III-nitrides are elastically anisotropic, so their values depend on crystal orientation, structure, and stress. Cubic (zincblende) nitrides have higher crystal symmetry than their wurtzite counterparts, which simplifies orientation-dependent interpretation; nevertheless, their indentation response may still exhibit elastic anisotropy, and film thickness and defect structure remain important.

The three source studies followed a broadly harmonized nanoindentation protocol. In all cases, measurements were performed using a Berkovich diamond indenter, the resulting load–displacement data were analyzed through the Oliver–Pharr method, and the

film surfaces were polished prior to testing. The indentation imprints were separated by 4  $\mu\text{m}$ , and loading and unloading times of 5 s each were used. For c-GaN, 25 indentations were performed using loads between 2.5 and 10 mN. For each  $\text{c-In}_x\text{Ga}_{1-x}\text{N}$  composition, 25 indentations were conducted over a 0.25–10 mN load range using continuous stiffness measurement (CSM) mode. For c-InN, 25 indentations were similarly performed over a 0.25–10 mN load range using CSM mode. The mechanical-property values compiled in this review correspond to the mean values obtained from the indentation sets, and the reported uncertainties represent the standard deviation.

These factors justify the intentional limitation of the wurtzite benchmark included later in this review, which serves solely as a contextual reference. The primary quantitative foundation of the review is the internally consistent dataset from Refs. [8–10], which use a common MgO/c-GaN-based platform, consistent Berkovich indentation and Oliver–Pharr analysis, and documented surface preparation conditions. This approach enables composition-aware cross-comparison across c-GaN,  $\text{c-In}_x\text{Ga}_{1-x}\text{N}$ , and c-InN without the confounding variables that render broader literature comparisons less straightforward.

Figure 3 shows representative measurements from the source studies. Figure 3a presents a typical indentation array on a polished surface, showing good spacing and repeatability. Figure 3b shows a selected atomic force microscopy (AFM) topographic map, while Figure 3c presents surface-profile traces that highlight imprint depth and contact morphology. Figure 3d shows a representative load–displacement curve, including an elastic–plastic transition and a pop-in event. Together, these examples support the careful interpretation criteria, especially the depth-window rule, used in the rest of the review.



**Figure 3.** Representative nanoindentation measurements associated with the datasets consolidated in this review. (a) AFM image showing a representative indentation array and spacing. (b) AFM topographic map of a selected indentation region, including the corresponding height scale. (c) Surface-profile traces across representative indentation imprints for different applied loads, highlighting the load dependence of imprint depth and morphology. (d) Representative load–displacement curve illustrating the elastic–plastic response and a pop-in event. Panel (a) is based on Ref. [8] (preprint). Panels (b–d) were adapted with permission from Refs. [9,10].

## 4. Consolidated Mechanical Properties Dataset

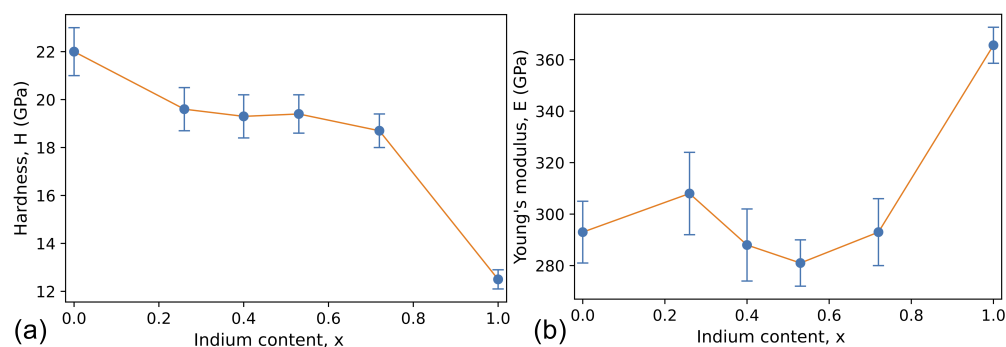
### 4.1. Consolidated Summary Table

Table 1 summarizes the hardness and Young’s modulus data, obtained by nanoindentation, for the complete series of cubic III-nitrides on MgO(001)-based templates: c-GaN,  $\text{c-In}_x\text{Ga}_{1-x}\text{N}$  alloys ( $x = 0.26$ – $0.72$ ), and c-InN. In addition to the mechanical values and their uncertainties, the table provides the epitaxial layer thickness, post-polishing RMS roughness, buffer layer configuration, and Poisson’s ratio for each case. These data are essential for assessing the comparability between different alloy samples. All films share the advantage of using the same MgO/c-GaN structure and were characterized by Berkovich indentation with Oliver–Pharr analysis, establishing an internally consistent framework for this compilation.

Figure 4 shows the consolidated hardness ( $H$ ) and elastic modulus ( $E$ ) values as a function of the indium content of the alloy. Figure 4a shows that the hardness remains



almost constant across the entire  $\text{c-In}_x\text{Ga}_{1-x}\text{N}$  alloy range (approximately 19 GPa), with a marked decrease only at the  $\text{c-InN}$  end ( $12.5 \pm 0.4$  GPa). The value for  $\text{c-GaN}$  ( $22 \pm 1$  GPa) marks the Ga-rich limit. In contrast, Figure 4b shows that the elastic modulus decreases from approximately 308 GPa at  $x = 0.26$  to a minimum of approximately 281 GPa at  $x = 0.53$ , followed by a partial recovery to approximately 293 GPa at  $x = 0.72$  and a sharp increase at the  $\text{c-InN}$  end ( $365.6 \pm 7$  GPa). This departure from the alloy trend indicates a distinct elastic response at the  $\text{InN}$  binary composition. These compositional observations are examined in more detail in the next subsection, focusing on depth dependence.



**Figure 4.** Consolidated hardness (a) and Young's modulus (b) as functions of indium content,  $x$ , for cubic III-nitrides on  $\text{MgO}(001)$ -based templates, spanning  $\text{c-GaN}$ ,  $\text{c-In}_x\text{Ga}_{1-x}\text{N}$  alloys, and  $\text{c-InN}$ .

#### 4.2. Depth Dependence of $H$ and $E$ : Film-Dominated Regime and Template Effects

The depth dependence of hardness and elastic modulus varies systematically among the three members of the cubic series. These differences reflect variations in epilayer thickness, modulus contrast with the underlying  $\text{c-GaN}$  template, and defect microstructure near the heteroepitaxial interfaces.

For  $\text{c-GaN}$ , the two film thicknesses studied (350 nm and 700 nm) provide direct evidence of thickness-dependent behavior. In the 700 nm film, both hardness and elastic modulus remain essentially constant over the accessible depth range (20–120 nm), remaining within the film-dominated regime even at penetrations exceeding 10% of the film thickness. This stability allows reliable extraction of intrinsic film properties:  $H = 22 \pm 1$  GPa and  $E = 293 \pm 12$  GPa. In contrast, the 350 nm film exhibits greater scatter in both quantities at deeper penetrations, attributed to the indenter's proximity to the  $\text{c-GaN}/\text{MgO}$  interface, where the elevated defect density due to lattice mismatch results in greater scatter. Pop-in events, defined as abrupt displacement bursts during loading, were observed exclusively in the 350 nm film at depths exceeding 110 nm. These events are attributed to indenter interaction with mismatch-generated defects rather than indentation-induced phase transformations. The absence of pop-in in the 700 nm film is consistent with the lower defect density away from the interface, as stacking faults in cubic GaN partially annihilate with increasing epilayer thickness. In both cases, the elastic modulus shows a slight upward trend with depth, which is explained by the similarity of the  $\text{MgO}$  elastic modulus to that of  $\text{c-GaN}$  rather than by a genuine substrate artifact.

For  $\text{c-InN}$  (epitaxial layer thickness approximately 180 nm over a 350 nm  $\text{c-GaN}$  buffer), the thinner geometry requires a shallower penetration window. A minimum penetration depth of 50 nm was established to avoid tip rounding artifacts at shallow depths, while the upper limit was set well below the  $\text{c-InN}/\text{c-GaN}$  interface. Within this window, the hardness remains relatively stable, resulting in  $H = 12.5 \pm 0.4$  GPa as a representative value for the selected measurement window. In contrast, the elastic modulus exhibits a measurable upward trend with increasing depth, indicating a greater influence of the template as the indenter approaches the  $\text{c-InN}/\text{c-GaN}$  interface. However, the modulus value of  $365.6 \pm 7$  GPa obtained at selected depths is substantially higher than

the c-GaN template value (approximately 293 GPa), suggesting that the reported  $E$  is not governed solely by the c-GaN template, although residual template contributions cannot be fully excluded.

For c-In<sub>x</sub>Ga<sub>1-x</sub>N alloys (epilayer thickness 230–450 nm depending on composition), the mechanical response was evaluated within controlled shallow-depth intervals, reaching approximately 40 nm for the thinnest films. The conventional 10% criterion was used as a practical guideline rather than as a strict cutoff. The continuous stiffness measurement mode used in these experiments enabled real-time monitoring of hardness and elastic modulus as a function of depth. This approach enabled the detection of surface anomalies and the confirmation of the depth range over which film-dominated properties could be extracted. Hardness values of approximately 19 GPa remain stable across the alloy range. In contrast, the modulus decreases gradually from approximately 308 GPa at  $x = 0.26$  to approximately 281 GPa at  $x = 0.53$ , followed by a partial recovery to approximately 293 GPa at  $x = 0.72$ . Because the epilayer thickness also decreases with increasing indium content, composition and film-geometry effects cannot be completely decoupled, and some residual sensitivity to the underlying c-GaN template cannot be excluded for the thinnest films. Nevertheless, the depth-resolved measurements and shallow analysis intervals were used to minimize this contribution. The modest non-monotonic variation in modulus may also be influenced by changes in cubic phase fraction and structural quality across the alloy series.

Increasing the indium fraction changes the average bonding environment, lattice parameter, local atomic arrangement, and elastic response of the alloy. The measured properties may also be influenced by variations in cubic-phase fraction, structural quality, epilayer thickness, and template contribution across the series. These coupled factors are consistent with the nearly composition-independent hardness and the modest, non-monotonic variation observed in the elastic modulus.

Collectively, these depth-dependent observations demonstrate that hardness is the more robust quantity across the series, reaching a stable film-dominated plateau at relatively shallow depths. Hardness is less sensitive to template proximity than the elastic modulus. In contrast, the modulus requires more careful depth-window control, particularly for thinner epilayers such as c-InN and high-indium c-InGa<sub>N</sub>, where controlled indentation windows are essential to minimize systematic contributions from the underlying layer. Accordingly, the reported alloy values are interpreted as composition-associated trends within the common MgO/c-GaN-based architecture, rather than as purely intrinsic composition dependences entirely independent of film thickness and template influence.

## 5. Benchmarking in the Broader Context of III-Nitride Materials

Table 2 presents a targeted set of nanoindentation values for representative wurtzite III-nitrides—h-GaN, h-In<sub>x</sub>Ga<sub>1-x</sub>N, and h-InN—selected to bracket the mechanical range of the hexagonal phase rather than to constitute an exhaustive survey. The selection prioritizes studies reporting both  $H$  and  $E$  with documented growth methods and explicit uncertainties, enabling an order-of-magnitude comparison with the cubic dataset in Table 1.

Table 3 gives a summary of these comparisons as typical ranges. For GaN, h-GaN values are usually between  $H \approx 15.9$ –20 GPa and  $E \approx 286$ –395 GPa. This means c-GaN ( $H = 22 \pm 1$  GPa,  $E = 293 \pm 12$  GPa) is at or above the highest hardness seen in the hexagonal range. For the alloys, cubic InGa<sub>N</sub> (about 19 GPa) is consistently harder than h-InGa<sub>N</sub> at similar indium levels (16–17 GPa), though its elastic modulus is within or below the hexagonal range. For InN, the difference is even clearer: c-InN hardness ( $12.5 \pm 0.4$  GPa) is higher than the selected h-InN benchmark values (4.5–8.8 GPa), and its extracted modulus ( $365.6 \pm 7$  GPa) is much higher than the selected hexagonal values (171–184 GPa). These

differences probably come from a mix of structure, composition, and testing methods, not just the phase. So, direct comparisons between phases should be made carefully. The cubic data in Table 1 remain the main reference for this review.

**Table 2.** Representative nanoindentation-derived mechanical properties for wurtzite III-nitrides. Values depend on depth, substrate, orientation, and analysis protocol; see cited works for details. MOCVD, metalorganic chemical vapor deposition; PAMBE, plasma-assisted molecular beam epitaxy.

| Material | Growth/Substrate                             | $t$ ( $\mu\text{m}$ ) | $H$ (GPa)        | $E$ (GPa)        | Notes                                      | Ref. |
|----------|----------------------------------------------|-----------------------|------------------|------------------|--------------------------------------------|------|
| GaN      | bulk crystal                                 | –                     | 20               | 295              | Bulk GaN nanoindentation.                  | [20] |
| GaN      | thin film                                    | –                     | $19 \pm 1$       | $286 \pm 25$     | Berkovich; thin-film GaN.                  | [21] |
| GaN      | epilayer                                     | –                     | $15.9 \pm 0.8$   | $394.6 \pm 12$   | GaN epilayer.                              | [22] |
| InGaN    | MOCVD/sapphire                               | 0.4                   | $16.65 \pm 1.07$ | $375.9 \pm 23.1$ | $x = 0.25$ .                               | [23] |
| InGaN    | MOCVD/sapphire                               | 0.4                   | $16.49 \pm 0.99$ | $322.4 \pm 13.5$ | $x = 0.30$ .                               | [23] |
| InGaN    | MOCVD/sapphire                               | 0.4                   | $16.06 \pm 0.68$ | $374.0 \pm 28.3$ | $x = 0.34$ .                               | [23] |
| InGaN    | MOCVD/sapphire                               | –                     | 17.6–13.8        | 374.3–327.8      | Varies with $T_g$ (730–790 °C).            | [24] |
| InN      | PAMBE/sapphire                               | 1–4                   | $8.8 \pm 0.4$    | $184 \pm 5$      | In- and N-face; see Table II of Ref. [25]. | [25] |
| InN      | PAMBE/GaN/AlN/Al <sub>2</sub> O <sub>3</sub> | 0.3                   | $4.5 \pm 0.5$    | $171 \pm 8$      | Pop-in observed at optimum growth $T$ .    | [26] |

**Table 3.** Representative hardness and Young’s modulus values for wurtzite and cubic III-nitrides reported in the literature (indicative ranges). This table is meant for context and should remain secondary to Table 1.

| Material | Phase    | Growth/Substrate                       | $H$ (GPa)      | $E$ (GPa)     | Reference |
|----------|----------|----------------------------------------|----------------|---------------|-----------|
| GaN      | wurtzite | bulk/thin films/epilayers (indicative) | 15.9–20        | 286–395       | [20–22]   |
| InGaN    | wurtzite | MOCVD/sapphire (indicative)            | 13.8–17.6      | 322–376       | [23,24]   |
| InN      | wurtzite | MBE/sapphire or templates (indicative) | 4.5–8.8        | 171–184       | [25,26]   |
| GaN      | cubic    | PAMBE/MgO(001)                         | $22 \pm 1$     | $293 \pm 12$  | [9]       |
| InGaN    | cubic    | PAMBE/c-GaN/MgO(001)                   | $\sim 19$      | 281–308       | [8]       |
| InN      | cubic    | PAMBE/c-GaN/MgO(001)                   | $12.5 \pm 0.4$ | $365.6 \pm 7$ | [10]      |

## 6. Discussion

### 6.1. Composition Trends and Mechanical Figures of Merit

Two robust trends emerge from the consolidated dataset (Table 1, Figure 4). First, c-GaN presents the highest hardness ( $H = 22 \pm 1$  GPa) and a modulus of  $E = 293 \pm 12$  GPa. Second, c-In<sub>*x*</sub>Ga<sub>1–*x*</sub>N maintains comparatively high hardness across  $x = 0.26$ –0.72 ( $H \approx 19$  GPa) with only modest, non-monotonic compositional dependence in modulus ( $E = 281$ –308 GPa), while the c-InN endpoint exhibits a pronounced reduction in hardness ( $H = 12.5 \pm 0.4$  GPa) alongside a substantially higher modulus ( $E = 365.6 \pm 7$  GPa).

The dimensionless ratio  $H/E$  provides a compact metric for comparing resistance to contact-induced plasticity across the series [27]. It decreases from approximately 0.075 for c-GaN to 0.06–0.07 for c-In<sub>*x*</sub>Ga<sub>1–*x*</sub>N alloys, and drops to 0.034 for c-InN. This progression underscores a counterintuitive feature of the c-InN endpoint: despite its high elastic stiffness, its low  $H/E$  ratio indicates a greater susceptibility to plastic deformation under contact loading. From a processing standpoint, InN-rich cubic layers are therefore the most vulnerable to surface damage during polishing, lithography, and handling, even when the elastic modulus alone might suggest otherwise.

As a complementary mechanical figure of merit, the ratio  $H^3/E^2$  is commonly used as a comparative index of resistance to contact-induced plastic deformation and load-carrying capacity [28]. Using the consolidated values in Table 1,  $H^3/E^2$  is approximately 0.124 GPa for c-GaN, ranges from approximately 0.076 to 0.092 GPa for the c-In<sub>*x*</sub>Ga<sub>1–*x*</sub>N

alloys, and decreases markedly to approximately 0.0146 GPa for c-InN. This ranking is consistent with the  $H/E$  trend and further indicates that c-InN has the lowest comparative resistance to contact-induced plastic deformation within the investigated series. Because  $H^3/E^2$  depends quadratically on the elastic modulus, the c-InN value should be interpreted cautiously in view of the possible template contribution to its extracted modulus. Both  $H/E$  and  $H^3/E^2$  are therefore used here as comparative figures of merit within the internally consistent dataset, rather than as direct measures of fracture toughness, wear resistance, or service durability [29].

## 6.2. Benchmark-Informed Context and Limits of Comparison

Compared with representative wurtzite benchmarks (Table 2), the cubic values are broadly consistent in magnitude, though differences warrant cautious interpretation. For GaN,  $H \approx 22$  GPa lies slightly above the representative wurtzite hardness range, while  $E \approx 293$  GPa falls within the reported modulus range for wurtzite GaN under nanoindentation. This indicates that cubic GaN on MgO(001) can achieve mechanical figures of merit comparable to mainstream wurtzite platforms when surface preparation and indentation depth are carefully controlled. For c-In<sub>x</sub>Ga<sub>1-x</sub>N, the cubic alloy series ( $H \approx 19$  GPa;  $E \approx 280$ – $310$  GPa) shows consistently higher hardness than wurtzite InGaN at comparable indium concentrations, while modulus values overlap with or fall below the hexagonal range. Given that modulus is particularly sensitive to Poisson ratio assumptions, pile-up or sink-in geometry, and the effective indentation depth relative to film thickness [16,19], the most reliable cross-phase conclusion is comparative rather than absolute: within a common MgO/c-GaN-templated stack, c-In<sub>x</sub>Ga<sub>1-x</sub>N maintains high hardness across a wide compositional range with only moderate dependence on indium content.

For c-InN, the contrast with the hexagonal phase is the most pronounced in the dataset. Wurtzite InN typically yields  $H \sim 4$ – $9$  GPa and  $E \leq 200$  GPa depending on growth method and orientation, whereas c-InN shows  $H = 12.5 \pm 0.4$  GPa and  $E = 365.6 \pm 7$  GPa. The higher modulus of c-InN relative to both h-InN and the c-GaN template should be considered provisional until validated by additional datasets with explicit depth-window reporting and independent defect quantification, given the thin epilayer geometry and the measurable template influence on  $E$  identified in Section 4.2.

First-principles calculations provide a useful reference for evaluating the elastic response of the cubic series. For zinc-blende GaN, calculated polycrystalline Young's modulus values range from approximately 253 to 285 GPa, depending on the computational approximation, with the upper value agreeing well with the nanoindentation-derived result of  $293 \pm 12$  GPa reported here [30]. For zinc-blende In<sub>x</sub>Ga<sub>1-x</sub>N, composition-dependent calculations predict a general decrease in the elastic constants and derived effective modulus toward the InN-rich limit [31]. The experimental c-In<sub>x</sub>Ga<sub>1-x</sub>N values exhibit a comparatively flatter compositional dependence, whereas the c-InN endpoint lies substantially above the corresponding ideal-crystal predictions.

This comparison should be regarded as qualitative rather than strictly quantitative. First-principles calculations describe defect-free bulk crystals and commonly derive isotropic effective moduli from the calculated elastic constants, whereas nanoindentation of epitaxial (001) films probes an effective response that may depend on crystallographic anisotropy, residual strain, defect density, interfaces, film thickness, indentation depth, template coupling, and the assumed Poisson ratio [32]. In this context, the agreement obtained for c-GaN supports the consistency of the experimental methodology. For c-InN, however, the extracted value of  $365.6 \pm 7$  GPa should be regarded as an effective indentation-derived modulus within the selected depth window, rather than as a definitive intrinsic bulk value. Its magnitude relative to both theoretical predictions and the c-GaN

template therefore warrants independent verification using thicker films or complementary elastic-characterization techniques.

### 6.3. Implications for Processing and Heterostructure Design

The numbers in Table 1 are not just of academic interest—they connect directly to decisions made during processing. A few points are worth keeping in mind when working with these stacks.

Defects near the heteroepitaxial interfaces affect how the material responds to contact loading, and thinner films are more exposed to that influence. The greater scatter and pop-in activity seen in 350 nm c-GaN compared to the 700 nm film is a concrete example of this. Including pop-in statistics or spatial mapping in future datasets would help quantify how much the microstructure varies across compositions, which is currently unknown for the InGaN alloy series.

The  $H/E$  trend has a practical implication that is easy to miss. c-InN has a high elastic modulus, which might suggest it is mechanically robust. But its low  $H/E$  ratio suggests a greater tendency toward plastic deformation under relatively modest contact loads. Polishing conditions that work fine for c-GaN or the InGaN alloys may leave measurable damage on InN-rich layers. That asymmetry is worth accounting for explicitly when designing a processing sequence for a full cubic nitride stack.

The c-GaN template is not just a structural feature of the growth—it sets the mechanical baseline for everything deposited on top of it. Its thickness and cubic phase fraction determine how quickly template effects show up as the indentation depth increases, particularly in the thinnest epilayers. In that sense, template parameters are as much a metrology variable as they are a growth parameter.

## 7. Conclusions

This review consolidates nanoindentation-derived hardness and elastic modulus data for cubic III-nitrides grown by plasma-assisted MBE on MgO(001)-based templates, covering c-GaN, c-In<sub>x</sub>Ga<sub>1-x</sub>N alloys ( $x = 0.26$ – $0.72$ ), and c-InN. Drawing from three studies that share a common platform, consistent measurement protocol, and documented surface preparation, the compilation makes composition-aware comparison possible in a way that the individual studies could not.

Several things stand out from the analysis. Hardness is the more stable quantity across the series—it settles into a film-dominated value at relatively shallow depths and is less sensitive to what lies beneath than the elastic modulus is. The modulus needs more careful depth-window control, especially for the thinner epilayers. The  $H/E$  ratio adds something the individual hardness and modulus values do not: it flags c-InN as a particularly susceptible member of the series to contact-induced plastic deformation, despite having the highest extracted modulus. That is a counterintuitive result with direct consequences for how InN-rich layers should be handled during polishing and lithography. The c-In<sub>x</sub>Ga<sub>1-x</sub>N alloys, by contrast, maintain roughly constant hardness across a wide indium range, which makes them mechanically predictable candidates for heterostructure applications.

Comparing with representative wurtzite data shows that cubic III-nitrides on MgO(001) are mechanically comparable to their hexagonal counterparts, and at the InN endpoint the cubic values are substantially higher for both hardness and extracted modulus. This difference is notable, but the c-InN modulus in particular deserves further scrutiny given the thin epilayer geometry and the template influence identified in Section 4.2.

Looking ahead, expanding the dataset to more compositions, adding pop-in statistics as a microstructural diagnostic, and cross-checking the c-InN modulus with complementary



techniques would all strengthen the picture. The c-GaN template parameters—thickness and cubic fraction—also deserve more systematic attention as variables that shape the mechanical metrology of the entire stack, not just its structure.

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## References

- Li, G.; Wang, W.; Yang, W.; Lin, Y.; Wang, H.; Lin, Z.; Zhou, S. GaN-based light-emitting diodes on various substrates: A critical review. *Rep. Prog. Phys.* **2016**, *79*, 056501. [CrossRef] [PubMed]
- Huang, Y.; Hsiang, E.-L.; Deng, M.-Y.; Wu, S.-T. Mini-LED, Micro-LED and OLED displays: Present status and future perspectives. *Light Sci. Appl.* **2020**, *9*, 105. [CrossRef] [PubMed]
- Li, P.; Ewing, J.; Wong, M.S.; Yao, Y.; Li, H.; Gandrothula, S.; Smith, J.M.; Iza, M.; Nakamura, S.; DenBaars, S.P. Advances in InGaN-based RGB micro-light-emitting diodes for AR applications: Status and perspective. *APL Mater.* **2024**, *12*, 080901. [CrossRef]
- Zhao, X.; Sun, K.; Cui, S.; Tang, B.; Hu, H.; Zhou, S. Recent progress in long-wavelength InGaN light-emitting diodes from the perspective of epitaxial structure. *Adv. Photon. Res.* **2023**, *4*, 2300061. [CrossRef]
- Zhong, Y.; Zhang, J.; Wu, S.; Jia, L.; Yang, X.; Liu, Y.; Zhang, Y.; Sun, Q. A review on the GaN-on-Si power electronic devices. *Fundam. Res.* **2021**, *2*, 462–475. [CrossRef] [PubMed]
- Zhang, Y.; Dadgar, A.; Palacios, T. Gallium nitride vertical power devices on foreign substrates: A review and outlook. *J. Phys. D Appl. Phys.* **2018**, *51*, 273001. [CrossRef]
- Kozak, J.P.; Zhang, R.; Porter, M.; Song, Q.; Liu, J.; Wang, B.; Wang, R.; Saito, W.; Zhang, Y. Stability, Reliability, and Robustness of GaN Power Devices: A Review. *IEEE Trans. Power Electron.* **2023**, *38*, 8442–8471. [CrossRef]
- López-Luna, E.; García Hernández, S.A.; Vidal, M.A. Mechanical Properties of Cubic InGaN Alloys: Hardness and Elastic Modulus Characterization by Nanoindentation. Preprint Submitted to *Thin Solid Films*, 2025. SSRN. Available online: <https://ssrn.com/abstract=5298030> (accessed on 16 July 2026).
- García Hernández, S.A.; Compeán García, V.D.; López-Luna, E.; Vidal, M.A. Elastic modulus and hardness of cubic GaN grown by molecular beam epitaxy obtained by nanoindentation. *Thin Solid Films* **2020**, *699*, 137915. [CrossRef]
- García Hernández, S.A.; Compeán García, V.D.; Prado Navarrete, E.; López-Luna, E.; Vidal, M.A. Evaluation of nanoindentation characteristics of cubic InN epilayer grown by Molecular Beam Epitaxy. *Thin Solid Films* **2021**, *736*, 138910. [CrossRef]
- López-Luna, E.; Vidal, M.A. Review of the Properties of GaN, InN, and Their Alloys Obtained in Cubic Phase on MgO Substrates by Plasma-Enhanced Molecular Beam Epitaxy. *Crystals* **2024**, *14*, 801. [CrossRef]
- Powell, R.C.; Lee, N.-E.; Kim, Y.-W.; Greene, J.E. Heteroepitaxial wurtzite and zinc-blende structure GaN grown by reactive-ion molecular-beam epitaxy: Growth kinetics, microstructure, and properties. *J. Appl. Phys.* **1993**, *73*, 189–204. [CrossRef]
- Matsushita, K.; Matsuno, Y.; Hariu, T.; Shibata, Y. A comparative study of the deposition conditions in the plasma-assisted deposition of gallium nitride thin films. *Thin Solid Films* **1981**, *80*, 243–247. [CrossRef]
- Amano, H.; Sawaki, N.; Akasaki, I.; Toyoda, Y. Metalorganic vapor phase epitaxial growth of a high quality GaN film using an AlN buffer layer. *Appl. Phys. Lett.* **1986**, *48*, 353–355. [CrossRef]
- Inushima, T.; Mamutin, V.V.; Vekshin, V.A.; Ivanov, S.V.; Sakon, T.; Motokawa, M.; Ohoya, S. Physical properties of InN with the band gap energy of 1.1 eV. *J. Cryst. Growth* **2001**, *227–228*, 481–485. [CrossRef]
- Oliver, W.C.; Pharr, G.M. An improved technique for determining hardness and elastic modulus using load and displacement sensing indentation experiments. *J. Mater. Res.* **1992**, *7*, 1564–1583. [CrossRef]
- ISO 14577-1:2015; Metallic Materials—Instrumented Indentation Test for Hardness and Materials Parameters—Part 1: Test Method. ISO: Geneva, Switzerland, 2015.
- Fischer-Cripps, A.C. *Nanoindentation*, 3rd ed.; Springer: New York, NY, USA, 2011. [CrossRef]
- Saha, R.; Nix, W.D. Effects of the substrate on the determination of thin film mechanical properties by nanoindentation. *Acta Mater.* **2002**, *50*, 23–38. [CrossRef]

20. Nowak, R.; Pessa, M.; Suganuma, M.; Yoshida, Y. Elastic and plastic properties of GaN determined by nanoindentation. *Appl. Phys. Lett.* **1999**, *75*, 2070–2072. [[CrossRef](#)]
21. Tsai, C.H.; Jian, S.R.; Juang, J.Y. Berkovich nanoindentation and deformation mechanisms in GaN thin films. *Appl. Surf. Sci.* **2008**, *254*, 1997–2002. [[CrossRef](#)]
22. Lin, M.H.; Wen, H.C.; Huang, C.Y.; Jeng, Y.R.; Yau, W.H.; Wu, W.F.; Chou, C.P. Nanoindentation characterization of GaN epilayers on A-plane sapphire substrates. *Appl. Surf. Sci.* **2010**, *256*, 3464–3467. [[CrossRef](#)]
23. Geetha, D.; Joice Sophia, P.; Radhika, R.; Arivuoli, D. Evaluation of nanoindentation and nanoscratch characteristics of GaN/InGaN epilayers. *Mater. Sci. Eng. A* **2017**, *683*, 64–69. [[CrossRef](#)]
24. Jian, S.R.; Fang, T.H.; Chuu, D.S. Nanomechanical characterizations of InGaN thin films. *Appl. Surf. Sci.* **2006**, *252*, 3033–3042. [[CrossRef](#)]
25. Yonenaga, I.; Ohkubo, Y.; Deura, M.; Kutsukake, K.; Tokumoto, Y.; Ohno, Y.; Yoshikawa, A.; Wang, X.Q. Elastic properties of indium nitrides grown on sapphire substrates determined by nanoindentation: In comparison with other nitrides. *AIP Adv.* **2015**, *5*, 077131. [[CrossRef](#)]
26. Benzarti, Z.; Sekrafi, T.; Khalfallah, A.; Bougrioua, Z.; Vignaud, D.; Evaristo, M.; Cavaleiro, A. Growth temperature effect on physical and mechanical properties of nitrogen rich InN epilayers. *J. Alloys Compd.* **2021**, *885*, 160951. [[CrossRef](#)]
27. Leyland, A.; Matthews, A. On the significance of the  $H/E$  ratio in wear control: A nanocomposite coating approach to optimised tribological behaviour. *Wear* **2000**, *246*, 1–11. [[CrossRef](#)]
28. Beake, B.D. The influence of the  $H/E$  ratio on wear resistance of coating systems—Insights from small-scale testing. *Surf. Coat. Technol.* **2022**, *442*, 128272. [[CrossRef](#)]
29. Chen, X.; Du, Y.; Chung, Y.-W. Commentary on using  $H/E$  and  $H^3/E^2$  as proxies for fracture toughness of hard coatings. *Thin Solid Films* **2019**, *688*, 137265. [[CrossRef](#)]
30. Qin, H.; Luan, X.; Feng, C.; Yang, D.; Zhang, G. Mechanical, thermodynamic and electronic properties of wurtzite and zinc-blende GaN crystals. *Materials* **2017**, *10*, 1419. [[CrossRef](#)] [[PubMed](#)]
31. Scharoch, P.; Winiarski, M.J.; Polak, M.P. Ab initio study of  $\text{In}_x\text{Ga}_{1-x}\text{N}$ —Performance of the alchemical mixing approximation. *Comput. Mater. Sci.* **2014**, *81*, 358–365. [[CrossRef](#)]
32. Vlassak, J.J.; Nix, W.D. Measuring the elastic properties of anisotropic materials by means of indentation experiments. *J. Mech. Phys. Solids* **1994**, *42*, 1223–1245. [[CrossRef](#)]

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