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Comment on "Structural and optical characterization of thin AlInN films on c-plane GaN substrates" [J. Appl. Phys. 134, 075301 (2023)]

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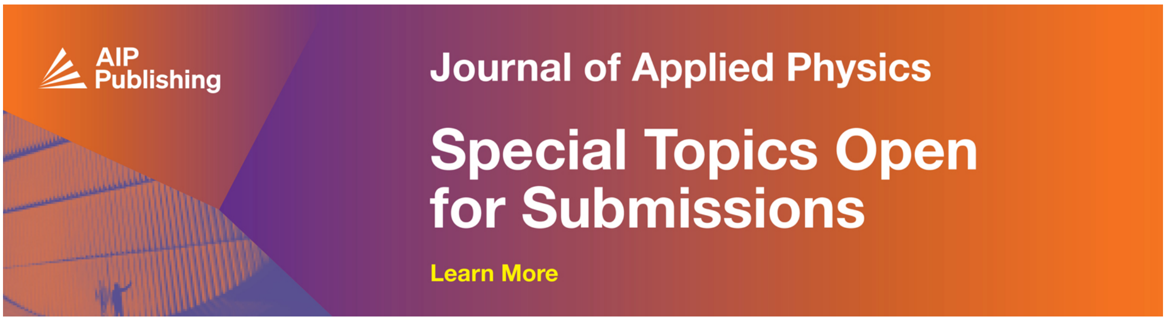

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AFFILIATIONS

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This comment further analyzes the refractive index of nearly-lattice-matched AlInN films using the original data from Xue *et al.*, J. Appl. Phys. **134**, 075301 (2023). It presents analytical equations to determine the refractive index of $Al_xIn_{1-x}N$ grown pseudomorphic to GaN substrates with x from 0.14 to 0.225 and wavelengths from 350 to 650 nm. These equations are useful for device designs using AlInN films.

In the study by Xue *et al.*,[1] ~30 nm thick $Al_{1-x}In_xN$ films are grown by metal-organic chemical vapor deposition on GaN substrates, and spectroscopic ellipsometry is used to determine the index of refraction and bandgap energy vs indium content (x) and wavelength (λ). These layers are pseudomorphic to the underlying GaN and exhibit smooth surfaces (rms < 0.29 nm) with minimum pit areas, attesting to their good crystallinity. Excellent empirical fits to bandgap energy (E_g) vs x data are achieved when considering the strain in the films and using Vegard's law and single bowing parameter of 3.19 eV. Accurate values for n and bandgap energy are helpful for optoelectronic device design. However, Ref. 1 lacks an analytical equation for the refractive index as a function of wavelength and composition, $n(x, \lambda)$, for below bandgap light in the visible spectrum, which this comment addresses.

The refractive index of a direct bandgap, ternary semiconductor for light with energies below the bandgap can be written as[2–4]

$$n(x,\lambda) = A(x)\cdot\left(\frac{E_g(x)}{E(\lambda)}\right)^2\cdot\left[2-\sqrt{1+\left(\frac{E(\lambda)}{E_g(x)}\right)}-\sqrt{1-\left(\frac{E(\lambda)}{E_g}\right)}\right]+B(x), \quad (1)$$

where $E(\lambda)$ is the energy of light, $A(x)$ has contributions from the electron and hole masses, the momentum matrix, and the bandgap, and $B(x)$ is determined by contributions for transitions above the absorption edge.[3] It is assumed the semiconductor has parabolic conduction and valence bands. The bandgap dependence on alloy fraction is expressed as

$$E_g(x) = (1-x)E_{g,\mathrm{AlN}} + xE_{g,\mathrm{InN}} - bx(x-1), \quad (2)$$

where $E_{g,\mathrm{AlN}}$ is the bandgap for AlN $E_{g,\mathrm{InN}}$ is the bandgap for InN, both are formed pseudomorphic to GaN, and b is the empirical bowing parameter. It was shown that when using $E_{g,\mathrm{AlN}}$ of 5.9 eV, $E_{g,\mathrm{InN}}$ of 0.2 eV, and $b = 3.19$ eV provides excellent fits to the bandgaps of pseudomorphic AlInN films grown on GaN substrates.[1]

Using functional values for $A(x)$ and $B(x)$, the refractive index of AlInN can be specified in terms of the alloy content,[2] as shown previously for AlGaN.[5–7] The coefficients are found the following way. First, Eqs. (1) and (2) are fit to the experimentally obtained refractive index values of the AlInN films as a function of the

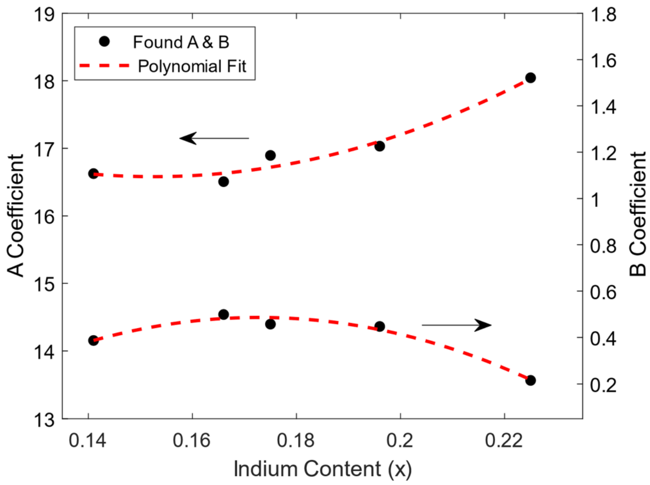

FIG. 1. A and B coefficients vs indium content (x), as determined from fitting. The dots are from fitting the experimental refractive index data using Eqs. (1) and (2), and dashed lines are polynomial fits to the A and B coefficients using Eqs. (3) and (4).

incident light wavelength ($\lambda = 350$–650 nm) using a nonlinear regression model. This is performed for the five indium content films (x = 0.14–0.225), creating a set of A and B for each x. Following this, the extracted coefficients are plotted vs x and fit using a polynomial function to determine the expression that characterizes the coefficient's dependency on the indium content, resulting in the following equations:

$$A(x) = 276.04x^2 - 84.215x + 23.004\,, \tag{3}$$

$$B(x) = -98.15x^2 + 33.916x - 2.4438\,. \tag{4}$$

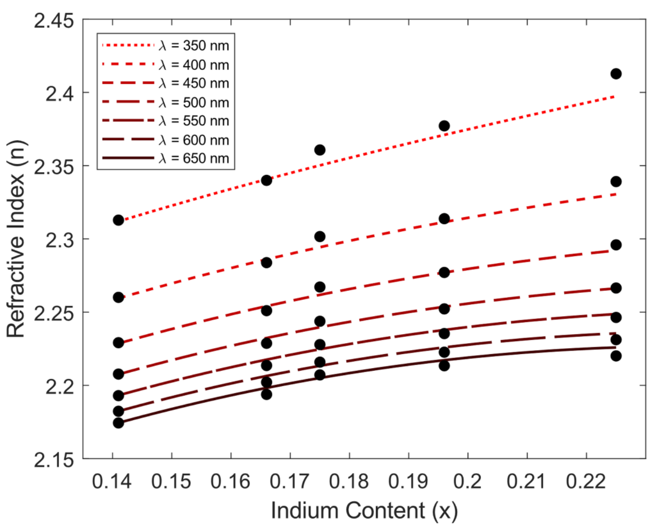

FIG. 2. Refractive index (n) vs indium content (x) as determined from fitting for wavelengths ranging from 350–650 nm. The circles are experimental data at each wavelength and x, while the lines are the results from the fit using Eqs. (1)–(4).

Figure 1 plots the A and B coefficients vs indium content, with the dashed red line showing the fit to the extracted coefficients.

Finally, Fig. 2 shows the refractive index vs indium content using Eqs. (1)–(4). The calculated curves show good agreement with the experimental data. An expected increase in refractive index with increasing indium content and photon energy is shown. There is a larger difference between the data and fit at $x = 0.225$. This high Al-content film has the largest strain of the set, which may account for this discrepancy.

This comment provides an analytical equation for the refractive index of AlInN as a function of wavelength and composition, $n(x,\lambda)$, in the visible spectrum, supplementing previously reported data.[1] These equations are useful for the design of visible spectrum optoelectronic devices using AlInN films, such as in-plane and vertical-cavity surface-emitting lasers.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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