On the environmental stability of ZnO thin films by spatial atomic layer deposition

Citation for published version (APA):

Illiberi, A., Scherpenborg, R., Theelen, M., Poodt, P., & Roozeboom, F. (2013). On the environmental stability of ZnO thin films by spatial atomic layer deposition. *Journal of Vacuum Science and Technology A: Vacuum, Surfaces, and Films*, 31(1), 061504-1-8. <https://doi.org/10.1116/1.4816354>

DOI:

[10.1116/1.4816354](https://doi.org/10.1116/1.4816354)

Document status and date:

Published: 01/01/2013

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

On the environmental stability of ZnO thin films by spatial atomic layer deposition

Andrea Illiberi, Robert Scherpenborg, Mirjam Theelen, Paul Poodt, and Fred Roozeboom

Citation: *Journal of Vacuum Science & Technology A* **31**, 061504 (2013); doi: 10.1116/1.4816354

View online: <http://dx.doi.org/10.1116/1.4816354>

View Table of Contents: <http://scitation.aip.org/content/avs/journal/jvsta/31/6?ver=pdfcov>

Published by the AVS: Science & Technology of Materials, Interfaces, and Processing

Instruments for advanced science

Gas Analysis

- dynamic measurement of reaction gas streams
- catalysis and thermal analysis
- molecular beam studies
- dissolved species probes
- fermentation, environmental and ecological studies

Surface Science

- UHV TPD
- SIMS
- end point detection in ion beam etch
- elemental imaging - surface mapping

Plasma Diagnostics

- plasma source characterization
- etch and deposition process reaction kinetic studies
- analysis of neutral and radical species

Vacuum Analysis

- partial pressure measurement and control of process gases
- reactive sputter process control
- vacuum diagnostics
- vacuum coating process monitoring

contact Hiden Analytical for further details

HIDEN
ANALYTICAL

info@hideninc.com

www.HidenAnalytical.com

CLICK to view our product catalogue

On the environmental stability of ZnO thin films by spatial atomic layer deposition

Andrea Illiberi,^{a)} Robert Scherpenborg, Mirjam Theelen, and Paul Poodt
 TNO Thin Films Technology Department, 5600 HE Eindhoven, The Netherlands

Fred Roozeboom

TNO Thin Films Technology Department, 5600 HE Eindhoven, The Netherlands and
 Department of Applied Physics, Eindhoven University of Technology, PO Box 513,
 5600 MB Eindhoven, The Netherlands

(Received 22 April 2013; accepted 9 July 2013; published 8 August 2013)

Undoped and indium-doped ZnO films have been deposited by atmospheric spatial atomic-layer-deposition (spatial-ALD). The stability of their electrical, optical, and structural properties has been investigated by a damp-heat test in an environment with 85% relative humidity at 85 °C. The resistivity of the ZnO films increased during damp-heat exposure mainly due to a sharp decrease in the carrier mobility, while the carrier density and transparency degraded only partially. The increase in resistivity can be ascribed to a degradation of the structural properties of ZnO films, resulting in a higher level of tensile stress, as indicated by x-ray diffraction analysis, and in a reduced near-ultraviolet emission level in their photoluminescence spectra. Al₂O₃ thin (25–75 nm) films grown by spatial-ALD at 0.2 nm/s are used as moisture barrier to effectively enhance the stability of the electrical and structural properties of the films. © 2013 American Vacuum Society. [<http://dx.doi.org/10.1116/1.4816354>]

I. INTRODUCTION

In recent years, the fast growth of the electronics and solar industry has led to an increasing interest in transparent and conductive oxides (TCOs).^{1,2} In particular, ZnO thin-films are emerging as an alternative TCO to the commonly used indium tin oxide, combining low costs with low toxicity, ease of fabrication, and patterning.^{3,4} However, the electrical resistivity of ZnO films increases significantly in harsh environments (i.e., annealing in air or humidity damping), thus hindering a widespread use of ZnO films in devices that require long-term reliability.^{5,6}

The industrial needs for deposition processes with high-throughput, low production costs, and no damage to the substrate (e.g., no bombardment by energetic ions) has driven the development of alternative techniques to sputtering for the growth of TCOs, such as atmospheric pressure CVD, low pressure expanding-thermal-plasma metalorganic-CVD, atmospheric pressure PE-CVD, and atmospheric pressure spatial atomic-layer-deposition (spatial-ALD).^{7–10} Spatial-ALD combines the advantages of conventional ALD (e.g., superior control of film composition, growth of uniform, pinhole free, and highly conformal thin-films on large area and flexible substrates) with high deposition rates (up to ~nm/s).¹¹ For this reason, atmospheric pressure spatial-ALD is emerging as an industrially scalable technique for the deposition of thin film electrodes (e.g., ZnO) and encapsulation (e.g., by Al₂O₃ thin-films) of solar and electronic devices.^{10,12}

In this paper, we report on the stability of the electrical, optical and structural properties of spatial-ALD intrinsic (i-ZnO) and In-doped ZnO (In:ZnO) films, exposed to a high

humidity and high temperature environment [85% relative humidity (RH), 85 °C]. The effect of spatial-ALD Al₂O₃ thin film encapsulation in enhancing the stability of ZnO films has also been tested.

II. EXPERIMENT

A schematic of the atmospheric spatial-ALD reactor used for the deposition is shown in Fig. 1. Two different inlets are installed in the circular reactor head, one for the metal precursors and another for the oxygen precursor. The substrate is placed on a circular table which rotates underneath the reactor head. During each rotation, the substrate is exposed sequentially to each precursor. Between and around the reactant inlets, shields of inert gas (N₂) separate the precursor flows and seal off the reaction zones, thus making the reactor completely independent of the environment, enabling operation under atmospheric pressure conditions. The entire reactor is installed in a conventional oven, which can be heated up to 400 °C.

For the conditions reported in this paper, diethyl zinc [Zn(C₂H₅)₂, (DEZ)], trimethyl indium [In(CH₃)₃, (TMIn)], and water (H₂O) vapor have been used as zinc, indium, and oxygen precursor, respectively. Metal precursors and water are evaporated from bubblers, by using argon as carrier gas and transported to the reactor head through heated lines, to prevent condensation. The DEZ and TMIn bubblers are heated in thermostatic water baths at 32 °C in order to control the vapor pressure of the precursors, while the H₂O bubbler is kept at 50 °C.

The argon flow through the H₂O and DEZ bubbler is set at 1 and 0.070 slm, respectively, while the argon flow through the TMIn bubbler has been varied, as: 0, 0.0025, 0.030, and 0.100 slm, with the aim of varying the In content

^{a)}Electronic mail: andrea.illiberi@tno.nl

FIG. 1. (Color online) (a) Schematic drawing of the spatial ALD reactor, where the DEZ, TMIn, and water half-reaction zones are separated by gas bearings. By moving the substrate underneath the reactor, the two half-reactions will take place subsequently to form a ZnO monolayer. (b) Schematic drawing of the bottom side of the spatial ALD reactor head, where the DEZ, TMIn, and water half-reaction zones are integrated into inlets surrounded by exhaust zones and gas bearing planes. The colors correspond to (a). (c) Schematic drawing of the reactor.

in ZnO films. The flows from the DEZ and TMIn bubblers are mixed and injected in the deposition zone through the same inlet, after being diluted by argon. The dilution flow is adjusted as: 0.927, 0.900, and 0.830 slm for each value of argon flow through the TMIn bubbler, so that the total flow in the inlet is kept constant at 1 slm. The kinetics of the surface reactions determining the In and Zn content of the films for different values of TMIn and DEZ partial pressure is currently under investigation, and it will be described in a future publication. The In:ZnO films have been deposited at a temperature of 200 °C, while i-ZnO was grown at 250 °C. A rotation frequency of 1.7 Hz was set for both undoped and In-doped ZnO films.

ZnO films have been deposited on $15 \times 15 \text{ cm}^2$ glass substrate (Schott AF 32) with pretreatment cleaning by ethanol, rinsed by water, and subsequent blow drying with nitrogen. The damp-heat test is carried out in a climate chamber with 85% RH at a temperature of 85 °C. The electrical, optical, and structural properties of the films have been measured after shortly taking the samples out of the climate chamber at different degradation times. After their characterization, the samples were placed back in the chamber to continue their degradation up to a total accumulated time of about 1000 h. The electrical properties and thickness of the films have been determined by using a Phystech RH 2010 Hall effect measurement, a Jandel universal four-point probe and a Veeco Dektak 8 Advanced

Development Profiler, respectively. Film optical properties have been measured in the near-ultraviolet, visible, and near-infrared by a UV-3600 Shimadzu spectrophotometer. The photoluminescence (PL) spectra have been measured by using a Xe lamp excitation with an excitation wavelength of 325 nm at room temperature. A Philips X-pert SR5068 powder diffractometer, equipped with a Cu-K α source, has been used to determine the crystallographic structure of the films. The zinc and indium content in the films has been measured in a FEI Quanta 600 FEG SEM system equipped with an energy dispersive x-ray (EDX) diagnostic.

III. RESULTS AND DISCUSSION

The electrical properties (i.e., resistivity, carrier density, and mobility) and In/Zn ratio of the as-deposited i-ZnO (ZO) and In:ZnO (IZO1, IZO2, IZO3) films are listed in Table I. Similar electrical properties are reported for intrinsic and doped ZnO films grown by conventional ALD.¹³ The resistivity (ρ) of the films is defined as: $\rho = R_s d$, being R_s the sheet resistance, measured by the four points probe and d the film thickness, measured by a profiler. All films have a thickness of about 250 nm. The values of resistivity for i-ZnO and In:ZnO films versus time in a 85 °C, 85% RH environment are reported in Fig. 2. The resistivity of both i-ZnO and In:ZnO films is

TABLE I. Electrical properties of as deposited *i*-ZnO (ZO) and In:ZnO (IZO1, IZO2, and IZO3) films calculated by Hall measurements. As reported in the table, the indium content has been increased by using a higher argon carrier flow, i.e., 0.0025, 0.030, and 0.100 slm, through the TMin bubbler. The indium/zinc ratio in the films has been measured by EDX analysis.

Sample	Ar flow (sccm)	In/Zn ratio (%)	Resistivity (Ω cm)	Carrier density (cm^{-3})	Mobility ($\text{cm}^2/\text{V s}$)
ZO	0	0	$3.8 \pm 1 \times 10^{-3}$	$7 \pm 1 \times 10^{19}$	28 ± 2
IZO1	0.0025	0.8	1.4×10^{-2}	1.4×10^{20}	3.13
IZO2	0.100	11	6.4×10^{-3}	2.8×10^{20}	3.33
IZO3	0.030	3	3.8×10^{-3}	6.1×10^{20}	2.69

found to increase with time. The values of carrier density and mobility during damp-heat exposure have been determined by Hall measurements and are plotted in Fig. 3. The carrier density is almost constant during the first 100 h of degradation, while the carrier mobility decreases in both *i*-ZnO and In:ZnO, thus resulting in a higher value of film resistivity, as shown in Fig. 2. The decrease in carrier mobility is particularly evident in films with a lower value of carrier density (e.g., ZO and IZO1), as also reported in Refs. 4 and 14 for CVD ZnO films. Hall measurements could not be performed for degradation times longer than about 100 h, due to the high values of sheet resistance (R_s) reached by the films ($R_s > 1000 \Omega/\text{sq}$).

The value of carrier density and effective mobility at longer degradation times have been calculated from the optical properties of the films. The band gap ($E_{g,\text{opt}}$) of degenerate ZnO films is known to have a systematic blue shift (the so-called Burstein-Moss effect¹⁵) with increasing carrier density (N_e), according to the relation

$$E_{g,\text{opt}} = E_g + (h/2\pi)^2 / (2m_e^*)(3\pi^2)^{2/3} N_e^{2/3}, \quad (1)$$

where $E_g = 3.2 \text{ eV}$ (Ref. 16) is the energy of conduction band edge with respect to the top of the valence band, m_e^* is the electron effective mass, and h is the Planck's constant. When accounting for the nonparabolic band structure of ZnO, the dependence of the effective mass on the electron energy in the conduction band ($E_{g,\text{opt}} - E_g$) can be approximated as

$$m_e^* = m_0^*[1 + 2\alpha_{np}(E_{g,\text{opt}} - E_g)]^{1/2}, \quad (2)$$

with m_0^* being the value of electrons' effective mass at the conduction band edge ($m_0^* = 0.35 m_e$, Ref. 16), α_{np} the non-parabolicity parameter ($\alpha_{np} \approx 1.04 \text{ eV}^{-1}$, Ref. 17) and $m_e = 9.1 \times 10^{-31} \text{ kg}$ the electron mass.^{18,19} The band gap ($E_{g,\text{opt}}$) of ZnO thin-films can be determined by using the relation

$$(\alpha h\nu)^2 \sim (h\nu - E_{g,\text{opt}}), \quad (3)$$

where the absorption coefficient (α) is calculated from the measured value of transparency (T), according to

$$\alpha = 1/d \ln(T), \quad (4)$$

with d being the film thickness.²⁰ The values of the absorption coefficient (α), electron effective mass (m_e^*), band gap ($E_{g,\text{opt}}$), and carrier density (N_e) can be calculated by solving the system of Eqs. (1)–(4). Knowing the value of carrier density (N_e) and the resistivity (ρ) of the films as measured by the four point probe, the effective mobility (μ_{eff}) of the carriers can be derived as

$$\mu_{\text{eff}} = 1/(\rho e N_e). \quad (5)$$

The transparency (T) and the squared value of the absorption coefficient (α^2) are plotted in Figs. 4 and 5, respectively, for as-deposited ZO and IZO films and after 1000 h at 85 °C and 85% RH. According to Eq. (3), the band gap ($E_{g,\text{opt}}$) of each

Fig. 2. (Color online) Resistivity vs time in 85 °C, 85% RH environment for *i*-ZnO (ZO) and In:ZnO films: IZO1 (0.8% In/Zn ratio), IZO2 (11% In/Zn ratio), and IZO3 (3% In/Zn ratio).

Fig. 3. (Color online) Density (a) and mobility (b) of charge carriers measured by Hall effect in *i*-ZnO and In:ZnO films.

FIG. 4. Transmittance of (a) as-deposited ZnO, (b) IZO1, (c) IZO2, (d) IZO3 and of films after 1000 h of exposure to 85% RH environment at 85 °C. The increased transparency in the near infrared range indicates a decrease in the value of carrier density during damp-heat exposure.

film has been calculated from the absorption coefficient (α^2) by the extrapolation method.¹⁹ By substituting the values of the band gap ($E_{g,opt}$) in Eq. (2), the effective mass (m_e^*) has been calculated for each film in the as deposited condition

and after 1000 h at 85 °C and 85% RH. Knowing the value of the effective mass (m_e^*), the carrier density (N_e) has been estimated from the Burstein–Moss effect, according to Eq. (1). The effective mobility (μ_{eff}) of the carriers is then

FIG. 5. Absorption coefficient (α) of (a) as-deposited ZnO, (b) IZO1, (c) IZO2, (d) IZO3 and of films after 1000 hours of exposure to 85% RH environment at 85 °C. The red shift of the band gap indicates a decrease in the value of carrier density during damp-heat exposure.

TABLE II. Electrical and optical properties of as deposited *i*-ZnO and In:ZnO films and of films after 1000 h of damp heat exposure, calculated by solving Eqs. (1)–(4).

Samples		As deposited films			After 1000 h of damp-heat exposure			
ID	$E_{g,opt}$ (eV)	Effective mass	N_e (cm ⁻³)	μ_{eff} (cm ² /Vs)	$E_{g,opt}$ (eV)	Effective mass	N_e (cm ⁻³)	μ_{eff} (cm ⁻² /Vs)
ZO	3.31	0.39	5×10^{19}	31	3.29	0.38	3×10^{19}	0.01
IZO1	3.43	0.49	2×10^{20}	3	3.30	0.42	4×10^{19}	0.2
IZO2	3.50	0.52	3×10^{20}	4	3.34	0.44	7×10^{19}	0.4
IZO3	3.67	0.60	7×10^{20}	3	3.54	0.54	4×10^{19}	0.5

calculated from Eq. (5). The values of band gap (E_g), electron effective mass (m_e^*), carrier density (N_e), and effective mobility (μ_{eff}) are listed in Table II for as-deposited and degraded films. The effective electron mass (m_e^*) is found to range from 0.35 to 0.6, according to the values reported typically in literature for ZnO films.¹⁷ The values of carrier density and effective mobility as calculated from the optical properties of the films are comparable with the values calculated by the Hall measurements in the as deposited films, shown in Table I.

The value of carrier density (N_e) decreases partially in both *i*-ZnO and In:ZnO after 1000 h of damp-heat exposure. The increase in film resistivity displayed in Fig. 2 is mainly driven by a sharp drop in the value of carrier mobility, as shown in Table II and in Fig. 3 for both *i*-ZnO and In:ZnO. A similar damp heat degradation behavior has been observed also for sputtered and CVD ZnO films by several authors.^{4,21–26} They propose that the diffusion of environmental gasses (e.g., oxygen, carbon dioxide, and water vapor) along the grain boundaries of ZnO films leads to a local increase in the density of traps states for the free carriers and in a higher potential barrier, which hinders the mobility of the carriers among the grains.¹⁴ The carriers flow across the grain boundaries via thermionic emission and tunneling increases with the Fermi level, and therefore, films with higher carrier density are typically found to have more stable electrical properties in a harsh environment, as also shown in Figs. 2 and 3.^{2,27}

The creation of crystallographic defects in ZnO films during damp-heat test has been investigated by both x-ray diffraction (XRD) and PL. The XRD spectra of *i*-ZnO (ZO) and In:ZnO (IZO1) films are shown in Fig. 6 for the as-deposited condition and at different degradation times. Although different crystallographic orientations are present, spatial-ALD ZnO and In:ZnO films have a (100) dominant orientation with a wurtzite crystal structure, as also reported in literature.¹⁰ With increasing time in a harsh environment, the peak position of (100) orientation shifts to lower angles for both *i*-ZnO and In:ZnO films, as shown in Fig. 6 for ZO and IZO3. A similar shift is observed for the other peaks in the XRD spectrum (not shown). This indicates that tensile stress is induced during damp-heat exposure by the formation of crystallographic defects in the lattice, which result from the diffusion of atmospheric gases in the bulk of the film, and a possible partial corrosion of the film surface.

The creation of photo-active defects in ZnO films during damp-heat test has been investigated by photoluminescence. The PL spectra of *i*-ZnO and In:ZnO films plotted in Fig. 7 show that as-deposited films are characterized by a strong UV (380–390 nm) and violet/blue (400–480 nm) and a less intense green/yellow emission band (500–600 nm). The UV emission is attributed to the band-edge transition, to the exciton recombination or to the electron transitions from a band of shallow defects levels to the valence band.²⁸ The violet/blue emission has been ascribed to different types (isolated and extended) of interstitial zinc, while the green emission is generated by the presence of oxygen vacancies.^{29,30} During damp-heat exposure, the intensity of the near-UV emission decreases sharply while the defects emission in the violet/blue and yellow/green range does not increase significantly in all the films. This indicates that crystallographic defects, such as zinc vacancies, are created in the films during damp-heat exposure, which can act as trap states and nonradiative recombination centers for the photoinduced electron–hole pairs.^{31,32}

The stability of the electrical and optical properties of ZnO can be enhanced when preventing a direct exposure of the film to atmosphere by using a moisture diffusion barrier.^{33,34} The Al₂O₃ is known to be an excellent gas diffusion barrier, capable of achieving intrinsic water vapor transmission rates (WVTR) in order of 10⁻⁵ g/m²/day when grown by conventional ALD.^{35–37} A similar value of intrinsic WVTR (10⁻⁵ g/m²/day) has been measured for spatial-ALD Al₂O₃ thin-films grown at ~0.2 nm/s and a temperature of

FIG. 6. (Color online) X-ray diffraction spectra of *i*-ZnO (ZO) and In:ZnO (IZO3) at different degradation times.

Fig. 7. Photoluminescence spectra of (a) *i*-ZnO, (b) IZO1, (c) IZO2, and (d) IZO3 for different exposure times at 85 °C and 85% RH.

200 °C, by using trimethylaluminum as aluminum precursor and water as oxygen precursor.¹² A complete description of the deposition process of Al₂O₃ by spatial-ALD can be found in Ref. 11. The effect of spatial-ALD Al₂O₃ thin film encapsulation on the stability of the electrical and optical properties of ZnO films has been tested. Spatial-ALD Al₂O₃ films with thicknesses of 25 or 75 nm have been grown on In:ZnO films (IZO3). The electrical, optical, and structural properties of bare and Al₂O₃-coated In:ZnO films have been measured at different degradation times in 85 °C, 85% RH environment. As shown in Fig. 8, the stability of the electrical properties of In:ZnO films improves sharply with increasing the thickness of Al₂O₃ film from 25 to 75 nm, possibly due to a better sealing of nanoparticles, present at the surface of ZnO, by the ALD film. When ZnO films are coated by a

75 nm thick Al₂O₃ film, the decrease in near UV emission in the PL spectra is strongly attenuated and the shift in the position of the main (100) crystallographic orientation is not detected by XRD, as shown in Fig. 9.

IV. SUMMARY AND CONCLUSIONS

Undoped (*i*-ZnO) and indium-doped ZnO (In:ZnO) films are deposited by the industrially scalable spatial-ALD technique. The stability of their electrical and structural properties in a harsh environment (85% RH, 85 °C) has been investigated. The resistance of both ZnO and In:ZnO films is found to increase during damp-heat exposure, mainly due to

Fig. 8. (Color online) Resistance vs time for In:ZnO films (IZO3) in a 85 °C, 85% RH environment with and without Al₂O₃ barrier film.

Fig. 9. (Color online) Photoluminescence and x-ray diffraction spectra of as deposited IZO3 film and Al₂O₃-coated IZO3 after 810 h of damp-heat exposure.

a reduction in carrier effective mobility. The increase in resistivity corresponds to a degradation of the structural properties of ZnO films, resulting in a higher tensile stress level, as indicated by XRD analysis, and in a lower intensity of near-UV emission in the photoluminescence spectra. The stability of ZnO films is sharply enhanced when coating them by a spatial-ALD Al₂O₃ moisture barrier. Being transparent in the visible range, spatial-ALD Al₂O₃ thin-films can be used to enhance the reliability of electronic devices in which ZnO thin-films are used as front electrode, such as chalcogenide-based (e.g., CIGS) solar cells.

ACKNOWLEDGMENTS

The authors acknowledge P. J. Bolt for coordinating and the European Commission for partially funding the presented work within the framework of the FP7 research project “Roll-to-roll manufacturing of high efficiency and low cost flexible CIGS solar modules” (grant agreement 283974 R2R-CIGS).

¹C. G. Granqvist, *Sol. Energy Mater. Sol. Cells* **91**, 1529 (2007).

²*Zinc Oxide: From Fundamental Properties Towards Novel Applications*, Springer Series in Materials Science, edited by C. F. Klinshirn, B. K. Meyer, A. Wang, A. Hoffmann, and J. Geurts (Springer, Heidelberg, Dordrecht, London, New York, 2010), Vol. 120, p. 120.

³T. Minami, *Thin Solid Films*, **516**, 5822 (2008).

⁴C. Guillen and J. Herrero, *Surf. Coat. Technol.* **201**, 309 (2006).

⁵D. W. Lee, O. Y. Kwon, J. K. Song, C. H. Park, K. E. Park, S. M. Nam, and Y. N. Kim, *Sol. Energy Mater. Sol. Cells* **105**, 15 (2012).

⁶M. Fakhri, H. Johann, P. Gorn, and T. Riedl, *ACS Appl. Mater. Interfaces* **4**, 4453 (2012).

⁷J. Hu and Roy G. Gordon, *J. Appl. Phys.* **72**, 5381 (1992).

⁸A. Illiberi, B. Kniknie, J. Van Deelen, H. L. A. H. Steijvers, D. Habets, P. J. P. M. Simons, A. C. Janssen, E. H. A. Beckers, *Sol. Energy Mater. Sol. Cells* **95**, 1955 (2011).

⁹I. Volintiru, M. Creatore, B. J. Kniknie, C. I. M. A. Spee, and M. C. M. van de Sanden, *J. Appl. Phys.* **102**, 043709 (2007).

¹⁰A. Illiberi, F. Roozeboom, and P. Poodt, *ACS Appl. Mater. Interfaces* **4**, 268 (2012).

¹¹P. Poodt, A. Lankhorst, F. Roozeboom, K. Spee, D. Maas, and A. Vermeer, *Adv. Mater.* **22**, 3564 (2010).

¹²P. Poodt, R. Knaapen, A. Illiberi, F. Roozeboom, and A. van Asten, *J. Vac. Sci. Technol. A* **30**(1), 01A142 (2012).

¹³Do-Joong Lee, Hyun-Mi Kim, Jang-Yeon Kwon, Hyoji Choi, Soo-Hyun Kim, and Ki-Bum Kim, *Adv. Funct. Mater.* **21**, 448 (2011).

¹⁴J. Steinhäuser, S. Meyer, M. Schwab, S. Faÿ, C. Ballif, U. Kroll, and D. Borrello, *Thin Solid Films* **520**, 558 (2011).

¹⁵M. Grundmann, *The Physics of Semiconductors* (Springer, Berlin, 2006), Vol. 9, p. 291.

¹⁶A. Sarkar, S. Ghosh, S. Chaudhuri, and A. K. Pal, *Thin Solid Films* **204**, 255 (1991).

¹⁷T. Minami, H. Sato, K. Ohashi, T. Tomofuji, and S. Takata, *J. Cryst. Growth* **117**, 370 (1992).

¹⁸J. S. Kim, J. H. Jeong, J. K. Park, Y. J. Baik, I. H. Kim, T. Y. Seong, and W. M. Kim, *J. Appl. Phys.* **111**, 123507 (2012).

¹⁹W. M. Kim, I. H. Kim, J. H. Ko, B. Cheong, T. S. Lee, K. S. Lee, D. Kim, and T. Y. Seong, *J. Phys. D.: Appl. Phys.* **41**, 195409 (2008).

²⁰A. Ohtomo, M. Kawasaki, T. Koida, K. Masubuchi, H. Koinuma, Y. Sakurai, Y. Yoshida, T. Yasuda, and Y. Segawa, *Appl. Phys. Lett.* **72**, 2466 (1998).

²¹O. Kluth, G. Schope, B. Rech, R. Menner, M. Oertel, K. Orgassa, and H. W. Schock, *Thin Solid Films* **502**, 311 (2006).

²²T. Tohsophon, J. Hupkes, S. Calnan, W. Reetz, B. Rech, W. Beyer, and N. Sirikulrat, *Thin Solid Films* **511**, 673 (2006).

²³T. Miyata, Y. Ohtani, T. Kuboi, and T. Minami, *Thin Solid Films* **516**, 1354 (2008).

²⁴D. Greiner, N. Papathanasiou, A. Pflug, F. Ruske, and R. Klenk, *Thin Solid Films* **517**, 2291 (2009).

²⁵J. Steinhäuser, S. Fay, N. Oliveira, E. Vallat-Sauvain, D. Zimin, U. Kroll, and C. Ballif, *Phys. Status Solidi A* **205**, 1983 (2008).

²⁶T. Minami, T. Kuboi, T. Miyata, and Y. Ohtani, *Phys. Status Solidi A* **205**, 255 (2008).

²⁷J. Y. W. Seto, *J. Appl. Phys.* **46**, 5247 (1975).

²⁸D. H. Zhang, Z. Y. Xue, and Q. P. Wang, *J. Phys. D: Appl. Phys.* **35**, 2837 (2002).

²⁹H. Zeng, G. Duan, Y. Li, S. Yang, X. Xu, and W. Cai, *Adv. Funct. Mater.* **20**, 561 (2010).

³⁰K. Vanheusden, C. H. Seager, W. L. Warren, D. R. Tallant, and J. A. Voigt, *Appl. Phys. Lett.* **68**, 403 (1996).

³¹T. Matsumoto, H. Kato, K. Miyamoto, M. Sano, E. A. Zhukov, and T. Yao, *Appl. Phys. Lett.* **81**, 1231 (2002).

³²N. T. Son *et al.*, *J. Appl. Phys.* **102**, 093504 (2007).

³³T. L. Chen, D. S. Ghosh, D. Krautz, S. Cheylan, and V. Pruneri, *Appl. Phys. Lett.* **99**, 093302 (2011).

³⁴T. L. Chen, D. S. Ghosh, N. Formica, and V. Pruneri, *Nanotechnology* **23**, 395603 (2012).

³⁵E. Langereis, M. Creatore, S. B. S. Heil, M. C. M. van de Sanden, and W. M. M. Kessels, *Appl. Phys. Lett.* **89**, 081915 (2006).

³⁶M. D. Groner, S. M. George, R. S. McLean, and P. F. Garcia, *Appl. Phys. Lett.* **88**, 051907 (2006).

³⁷P. F. Garcia, R. S. McLean, M. H. Reilly, M. D. Groner, and S. M. George, *Appl. Phys. Lett.* **89**, 031915 (2006).