Effect of substrate temperature on bismuth oxide thin films grown by pulsed laser deposition

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Abstract

We present and discuss on bismuth oxide films grown on cost-efficient BK7 glass slides by pulsed laser deposition using a metallic target. Our choice is of particular interest due to the high number of intermediate bismuth oxides that can form during the oxidation process, along with the polymorphs of the stoichiometric oxide, i.e. bismuth trioxide (Bi_2O_3). We show that the oxidation degree of bismuth increases with substrate temperature, t_s (300–600 °C), when grown in 100 sccm flow at 6×10^{-1} mbar O_2 partial pressure. Thin film crystallinity is also increased with t_s , as expected. Instead, the refractive index (n) of the films decreases in the visible range, as t_s is increased. Furthermore, the transmittance of the films increases with t_s to over 60%, especially in the red and near-infrared region (above 600 nm). As a final point, the results are discussed and compared to literature.

Keywords Thin films · Laser processing · Substrate temperature · Optical properties · Wemple-DiDomenico model

1 Introduction

The need for “use-and-throw” materials, for cost-efficient and/or eco-friendly sensors, electronics, and single use devices, led to a significant growth in the field of materials science, in particular for thin film and superlattices. Thin films are deposited onto bulk materials, i.e. a substrate, so as to achieve specific, required properties [1]. Even though several techniques are currently available, e.g. magnetron sputtering, spray pyrolysis, sol–gel, spin coating or drop-casting, or by electrochemical means, it’s still challenging to control the kinetics in order to grow high quality thin films. In particular, their adherence to the substrate, desired stoichiometry, reliability and reproducibility, are always a subject of concern [1–3]. In the case of oxides, their deposition as thin films or other very low-dimensional objects is even trickier, since the oxygen amount may be very different in the as-grown samples as

compared to the source material, due to either the oxygen loss/uptake in/from the surrounding environment or to the oxygen uptake from the substrate [4–7].

Historically, all the necessary ingredients for different vacuum-coating processes were present long before the actual processing techniques and methods [8]. However, understanding the mechanisms and the physical and chemical processes behind thin film deposition is rather new. By varying the oxygen content, it was found that a reduction of oxygen in the film leads to changes in both structural and optical characteristics [9]. When metal oxidation is employed for the preparation of oxide thin films, the chosen procedure and method, as well as the conditions that are set, are all crucial to the quality and properties of the resulting samples.

Thermal oxidation is a widely used method for the production of oxides of various metals, including bismuth [10]. The process is of high interest in the case of

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bismuth, given its variety of non-stoichiometric oxides that can form and coexist with the multiple polymorphs of the stoichiometric bismuth trioxide during and after the oxidation process. This often complex composition and structure of oxidized bismuth films leads to difficult interpretation and correlation with and between related to various physical properties such as electrical and optical ones. There are numerous reports in the scientific literature concerning bismuth oxide thin films obtained by thermal oxidation or by other methods, with films exhibiting various structures, morphologies, and optoelectronic properties. On the other hand, it was shown that the films evaporated from bulk Bi_2O_3 are prone to vary in stoichiometry [11]. To overcome such phenomena, we have recently revealed that stoichiometry control could be achieved through various techniques [12–24]. Usually, the as-prepared films are characterized by a mixture of polycrystalline and amorphous phases. Reports on the properties and applications of bismuth oxide nanoparticles, nanorods, nanowires, nanomesh, nanoplates and nanoflakes, and thin film nanocomposites are also found in literature [25–37].

As a bulk material, at least six polymorphs have been identified for the Bi_2O_3 composition. The stable phases are: α (monoclinic) from room temperature (RT) to about 729 °C, and δ (face centred cubic, *fcc*) above 730 °C up to 825 °C, i.e. the melting point of bismuth oxide. Two intermediate metastable polymorphs appear during cooling down from the δ -phase: β (tetragonal) and γ (body centred cubic, *bcc*). The transformation into these phases occurs around 650 °C and 640 °C, respectively, and it depends on the purity and texture of the samples. On cooling, δ - Bi_2O_3 transforms to α -phase through a series of metastable forms (β , γ) and the conductivity drops over three orders of magnitude. The stable δ - Bi_2O_3 can be obtained by means of the addition of other oxides such as WO_3 , Y_2O_3 and RE_2O_3 , where RE is a “rare earth” element. However, the conductivity drops by about two orders of magnitude. Consequently, the possibility of stabilizing pure δ - Bi_2O_3 has been doubted for some time. Recently, δ - Bi_2O_3 has been synthesized by electrodeposition and chemical vapour deposition. Other metastable phases, which have been obtained under special conditions, are ω (triclinic) and ϵ (orthorhombic), known as high temperature metastable phases. Such properties, i.e. large energy band gap, refractive index, dielectric permittivity as well as remarkable photoconductivity and photoluminescence [15, 38–41], make bismuth oxide an interesting candidate for applications in the fields such as optoelectronics, optical coatings, gas sensors, Schottky barrier solar cells, metal–insulator–semiconductor (MIS) capacitors, microwave integrated circuits, etc. Even so, their real use is less extensive since for such nanostructures one major issue is

to obtain a single stable phase needed in the technological applications.

Here, we propose pulsed laser deposition (PLD) as a technique of choice for growing high quality films, as it proves to be the most adequate in obtaining bismuth trioxide (Bi_2O_3) from metallic bismuth targets in a controlled oxygen atmosphere, onto BK7 glass substrates. We study the influence of temperature on the morphological, structural and optical properties of the films. The substrates used in studying the films are inert and non-interacting, known to deliver no noteworthy contribution to the optical properties to the subsequent investigations of the films. This study provides important insights on the growth and characterization of Bi_2O_3 thin films prepared by reactive PLD, and the structural and optical properties of the films are investigated and discussed. The influence of the substrate temperature was investigated with a constant partial pressure of oxygen, an essential step for understanding its effect on the phase components and crystalline structure of the bismuth oxide thin films.

2 Experimental

2.1 Materials and thin film growth

Bismuth oxide thin films have been prepared by PLD using a UV nanosecond pulsed laser (10 Hz repetition rate, 3.5 J/cm² fluence) from a pure bismuth target (99.99%, Sigma-Aldrich), in constant oxygen flow (6×10^{-1} mbar O_2 partial pressure). The thickness of the films is varied by simply changing the deposition time. Further details about the PLD technique employed for the deposition of bismuth oxide thin films are given elsewhere [20, 23]. The substrates, made of high-quality BK7 glass slides, have been thoroughly cleaned in an ultrasound bath using acetone, then ethanol, rinsed by water and finally blow-dry in argon flow. The temperature of the substrate (t_s) was varied, i.e. 300 °C, 400 °C, 500 °C and 600 °C, respectively. Several series of depositions have been made for statistical purpose. Film thickness was measured by means of a MII-4 Linnik-type interferential microscope operated with white light, by using the multiple-beam Fizeau fringe method. Structural analysis of the films was achieved through X-ray diffractometry (XRD), by using a DRON-3 diffractometer with a Co target ($\lambda = 1.789 \text{ \AA}$). Atomic force microscopy (AFM) was employed for morphological studies, with two-dimensional (2D) images and roughness parameters assessed. Because such films have already proven their potential application in optoelectronic applications, due to their high transmittance, high refractive index, and ease in tailoring the energy bandgap, a thorough optical analysis of our samples was performed. Transmittance and

reflectance measurements have been made by a Perkin Elmer Lambda 35 spectrophotometer operated in air, with an available spectral range between 190 nm and 1100 nm. The *Wemple-DiDomenico* model was applied to deduce the energy bandgap (E_g) of the films, along with the dispersion energy (E_d), which expresses the strength of the interband optical transitions [15, 42, 43].

3 Results and discussion

The present paper can be considered as an extension of our previous work, to demonstrate the efficiency of the PLD technique in producing high quality Bi_2O_3 thin films with or without the radio frequency (RF) power, as a deposition parameter to control O_2 reactivity [13, 15, 16, 20–22]. Here, we have studied in more detail the different Bi_2O_3 phases that can be obtained by using a metallic bismuth

target and by varying the substrate temperature. The different structures and both optical and morphological properties have been carefully assessed for each of the deposition conditions.

The structural analysis is the first step for assessing the properties of thin films and of their crystallinity degree. In our case, since vacuum oxidation was employed along with the PLD of pure bismuth targets, the XRD method also offers the possibility to assess the oxidation degree through the identification of the types of oxides and their corresponding crystalline planes producing the diffraction of incident X-rays, according to the *JCPDS* files [44]. In Fig. 1, we present the normalized XRD patterns of each of the 4 types of bismuth oxide films under study. One may notice that the films exhibit no trace of metallic bismuth, i.e. the thin films are completely oxidized. The films are polycrystalline and polymorph, with some amorphous phase remaining for lower substrate temperatures (i.e. at

Fig. 1 The X-ray diffraction (XRD) patterns of the bismuth oxide thin films grown at four different substrate temperatures: 300 °C (a), 400 °C (b), 500 °C (c), and 600 °C (d)

Fig. 2 Two-dimensional (2D) atomic force microscopy (AFM) images of the bismuth oxide thin films grown at four different substrate temperatures: 300 °C (**a**), 400 °C (**b**), 500 °C (**c**), and 600 °C (**d**)

Table 1 Roughness parameters of the bismuth oxide thin films under study

	Substrate temperature, t_s (°C)	Film thickness, d (μm)	Average peaks height, z_{average} (nm)	Mean roughness, R_a (nm)	RMS (nm)
1	300	0.406	16.300	4.474	5.724
2	400	0.389	17.264	4.679	5.893
3	500	0.476	19.562	5.318	6.795
4	600	0.529	29.808	7.412	9.319

300 °C - see Fig. 1a) and 400 °C (Fig. 1b), and much less for 500 °C (Fig. 1c) and above (at 600 °C, Fig. 1d) during the PLD process, identified as the “bump” (or high background) of the XRD spectra that is noticeable at low diffraction angles. Bismuth trioxide— Bi_2O_3 , however, appears only in films deposited at substrate temperatures above

400 °C. This leads us to the conclusion that only high temperatures inducing high mobility of the atoms provide the conditions for the stoichiometric oxide to form. But even so, all the investigated thin film samples exhibit a certain amount of co-existing non-stoichiometric oxides. Thus, the multiple coupling possibilities between bismuth

Fig. 3 The plot and fitting of three roughness parameters of the bismuth oxide thin films with respect to substrate temperature

and oxygen lead, during oxygen plasma-assisted bismuth target ablation, to the formation of a multitude of intermediate oxides, whose molecules collide even at room temperature, then they agglomerate while ‘condensing’ on the substrate, such that oxygen atoms could be exchanged between neighbouring molecules. This plausible behaviour is strongly influenced by the arrangement of the crystalline planes, through the ‘channels’ in-between that, if large enough, favour the movements of the oxide molecules and their reciprocal exchange of atoms.

Two polymorphs of Bi_2O_3 are observed, as the number of different types of crystalline planes is increasing with increasing substrate temperature during the PLD processes. The films deposited at 300 °C and 400 °C have the (111) planes of the Bi_2O_4 intermediate oxide in common, while the films deposited at 400 °C, 500 °C and 600 °C have in common the (201) planes of Bi_4O_7 , along with the (112) planes of the monoclinic alpha polymorph of Bi_2O_3 .

The best crystallinity and highest texturing degree for the film deposited at the highest substrate temperature: $t_s = 600$ °C. Thus, as in the case of thermal oxidation in air, bismuth presents a complicated composition and structure of intermediate oxides and some of the polymorphs of the stoichiometric bismuth trioxide. Even though the

structure is rather complicated, the films present remarkable properties and are suitable for specific applications, therefore justifying their study [14, 15, 38–41, 45–47].

To further investigate and understand the growth mechanisms, and to corroborate with the XRD data, in Fig. 2 we present the two-dimensional (2D) AFM images ($1\ \mu\text{m} \times 1\ \mu\text{m}$) of the four types of bismuth oxide thin films. Different scan lengths have been measured for all specimens as the roughness was shown to be influenced by the actual scanning size [48]. The micrographs reveal that surface of the films exhibits submicron grains, uniformly distributed. Table 1 reunites most relevant roughness parameters inferred from the AFM images, along with the thicknesses of the films [48–51]. The lower thickness of the film deposited at 400 °C might be given by the match between the crystalline arrangement of the composing oxides as compared to the other films that, even having fewer types of oxides as in the case of the film deposited at 300 °C, their structures don’t match and therefore won’t align to form a thin film. Thus, the film deposited at 400 °C contains monoclinic Bi_2O_4 and $\alpha\text{-Bi}_2\text{O}_3$, which can pair, as well as the other three component oxides, namely the tetragonal Bi_4O_7 , $\text{Bi}_2\text{O}_{2.33}$ and $\beta\text{-Bi}_2\text{O}_3$, respectively.

One may see from Table 1 that the films present peak heights of tens of nanometers that are enlarging with increasing t_s . The mean roughness, R_a and the root mean square roughness, RMS, are below 10 nm and also increase with increasing t_s . These values were estimated on the largest AFM scanned areas, as an evaluation over a series of samples for each temperature, with three different scanned areas on each sample. The monotonous variation of the selected roughness parameters with the substrate temperature during the deposition of the bismuth oxide films has led to the idea of plotting and fitting each of the parameters with respect to the t_s , as it can be seen in Fig. 3. Such dependency perfectly fit an exponential growth of the type:

$$y = y_0 + A \cdot \exp\left(\frac{x}{t}\right)$$

with y_0 , A and t as fitting parameters, as presented in Table 2. The errors are somewhat high for the ‘A’ parameter.

Table 2 The values of the fitting parameters, and the corresponding error, for each of the roughness parameters plotted with respect to substrate temperature

Roughness parameter	y_0 (nm)		A (nm)		t (nm)	
	Value	Standard error	Value	Standard error	Value	Standard error
Average peaks height, z_{average}	16.21	0.26	0.0035	0.0022	72.55	5.52
Mean roughness, R_a	5.57	0.09	0.0041	0.0024	87.84	7.47
Root mean square roughness, RMS	4.39	0.01	0.0026	0.0001	84.95	0.60

Fig. 4 Optical transmittance (a) and reflectance (b) spectra of the bismuth oxide thin films grown at four different substrate temperatures

Instead, the 'y₀' and 't' parameters present extremely low errors.

The optical analysis of the bismuth oxide thin films deposited by RF-PLD concerned not only the study of the wavelength dependence of the optical transmittance and reflectance (see Fig. 4), but also included the computation of the refractive index of each film, whose result is presented in Fig. 5.

The refractive index was computed as [14]:

$$n = \frac{1+R}{1-R} + \sqrt{\frac{4R}{(1-R)^2} - \bar{k}^2}$$

Fig. 5 Wavelength dependence of the refractive index for each type of bismuth oxide thin films grown at four different substrate temperatures

where R is the reflectance, and $\bar{k}$ is the absorption index related to the absorption coefficient (α) and wavelength (λ) through: $\bar{k} = \frac{\alpha \cdot \lambda}{4\pi}$.

While the absorption coefficient is inferred from the transmission and reflection data as [52]:

$\alpha = \frac{1}{d} \cdot \ln \left[\frac{(1-R)^2}{T} \right]$, with d —as the film thickness, R —the reflectance, and T —the transmittance.

From Fig. 4a, one may notice that all the studied films present high transmittance above 500 nm, while in the near infrared, the highest transmittance corresponds to the film with $t_s = 600^\circ\text{C}$. High transmittance for thin films can be associated with good crystallinity, while the narrower wavelength range with non-zero transmittance of the film deposited at 600°C can be related to the extremely complex composition and structure of the film, leading to internal reflections and transmittance loss, more accentuated as compared to the three other simpler type of films.

The much higher transmittance of the studied films as compared to their reflectance led us to rule out the influence of the backscattered light on the refractive index measurements.

The oscillating aspect of both the reflectance spectra, as seen in Fig. 4b, and of the wavelength dependence of the refractive index (Fig. 5) is due to the noteworthy homogeneity of the films, giving rise to multiple reflections and the interfaces and to their interference [53]. The highest reflectance and refractive index are reached for the films grown at the lowest substrate temperature (i.e. $t_s = 300^\circ\text{C}$), aspect related to their roughness which is the lowest of the four types of analyzed films, according to the AFM analysis as given in Fig. 2 and Table 1.

Fig. 6 Wemple-DiDomenico model for each type of bismuth oxide thin films grown at four different substrate temperatures: 300 °C (a), 400 °C (b), 500 °C (c), and 600 °C (d)

Finally, the Wemple-DiDomenico model was applied (see Fig. 6) in order to infer the most relevant parameter of a semiconducting film, namely the energy bandgap, E_g . This model which implies plotting a function of the refractive index, namely $1/(n^2 - 1)$ against the squares photon energy, $(h\nu)^2$ proves a good alternative for the Tauc model, since it allows scientists to infer not only E_g , but also the dispersion energy, E_d , expressing the strength of the inter-band optical transitions [14, 54–56]. Thus, the Wemple-DiDomenico formula relating the refractive index to the photon energy is: $n^2(\nu) = 1 + \frac{E_d \cdot E_0}{E_0^2 - (h\nu)^2}$.

With E_d —the dispersion energy, while E_0 is the oscillation energy, from which the energy bandgap can be computed as: $E_g = \frac{E_0}{2}$.

The resulting parameters of the Wemple-DiDomenico model applied for the bismuth oxide films under study are given in Table 3. Both Fig. 6 and the data from Table 3 demonstrate that the Wemple-DiDomenico model fits well on different spectral domains, as related to the composition and the structure of the films. The highest dispersion energies, E_d are obtained for the lowest t_s . Similar results were obtained by other scientists for oxide thin films [54–56].

The energy bandgaps of the bismuth oxide thin films range from 0.743 eV up till 3.312 eV, changing with

Table 3 The main resulting parameters from the Wemple-DiDomenico model when applied to the bismuth oxide thin films grown at four different substrate temperatures

Substrate temperature, t_s (°C)	Slope, a	Intercept, b	Energy bandgap, E_g (eV)	Dispersion energy, E_d (eV)
300	−0.103	0.428	1.017	4.753
	−0.013	0.224	2.094	18.681
	−0.012	0.528	3.312	12.558
400	−0.076	0.716	1.530	4.273
	−0.080	0.786	1.567	3.987
	−0.074	1.567	2.299	2.934
500	−0.087	0.898	1.608	3.583
	−0.039	1.066	2.601	4.882
600	−0.307	0.677	0.743	2.193
	−0.386	1.833	1.089	1.188
	−0.192	1.815	1.537	1.694
	−0.049	1.071	2.347	4.383

increasing substrate temperature during the depositions. The multiple values of the energy bandgap obtained for each of the films are related to their complex composition and structure that lead to complex energy bands structures, as well, such that electrons could jump from one energy level of a certain oxide to the energy level of another oxide. But especially given such complex energy bands structures, such films could prove sensitive to the electromagnetic radiation from a large spectral range, recommending them for various optoelectronic applications.

4 Conclusion

Bismuth oxide thin films are grown by pulsed laser deposition, starting from a metallic bismuth target in reactive oxygen plasma, on cost-efficient BK7 glass substrates at four temperatures varied between 300 °C and 600 °C. The structural, morphological and optical properties of the films are investigated. The substrate temperature during the preparation of bismuth oxide thin films outcomes as a crucial parameter in controlling their properties. The films prove to be polymorph, polycrystalline, containing intermediate bismuth oxides and with a more complex composition and structure as the substrate temperature is increased. The atomic force microscopy analysis reveals uniform grains on the surface of the films, sharper at the highest substrate temperature of 600 °C. The most relevant roughness parameters, namely the average peaks height, the mean roughness and the root mean square roughness increased exponentially with the substrate temperature. The optical parameters of the films also exhibited high sensitivity to substrate

temperature. Above 500 nm, the transmittance of the films is important, while the refractive index shows an oscillating dependence on wavelength similar to the reflectance spectra, due to the multiple reflections at the interfaces of the highly-uniformly deposited films. The *Wemple-DiDomenico* model was used in order to infer the energy bandgap for each film. More than one value for the energy bandgap was obtained for each of the films, due to their complex structure inducing a complex energy band structure. Multiple values of the energy bandgap for each film could prove useful for various optoelectronic applications, as the results indicate that the direct allowed transitions dominate in these bismuth oxides. The reflectance of thin bismuth oxide films depends on the substrate type and temperature, i.e. the small transparency of the thin films grown on glass is more related with large reflectance than absorption.

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Compliance with ethical standards

Conflict of interest The Authors declare that they have no conflict of interest.

References

- Martin PM (ed) (2010) Handbook of Deposition Technologies for Films and Coatings: Science, Applications and Technology, 3rd edn. Elsevier, New York. eBook ISBN 9780815520320
- Nikitenkov N (ed) (2017) Modern technologies for creating the thin-film systems and coatings. IntechOpen, Rejeka. <https://doi.org/10.5772/63326>. ISBN 978-953-51-3004-8
- Kaiser N (2002) Review of the fundamentals of thin-film growth. Appl Opt 41:3053–3060. <https://doi.org/10.1364/AO.41.003053>
- Schneider CW, Esposito M, Marozau I, Conder K, Doebeli M, Hu Y, Mallepell M, Wokaun A, Lippert T (2010) The origin of oxygen in oxide thin films: Role of the substrate. Appl Phys Lett 97:192107. <https://doi.org/10.1063/1.3515849>
- Scullin ML, Ravichandran J, Yu C, Huijben M, Seidel J, Majumdar A, Ramesh R (2010) Pulsed laser deposition-induced reduction of SrTiO₃ crystals. Acta Mater 58:457–463. <https://doi.org/10.1016/j.actamat.2009.09.024>

6. Jeong J (2018) Study on the effect of oxygen defects on the electrical and optical properties of thin films. Scanning. <https://doi.org/10.1155/2018/4592913>
7. Szwachta G, Kac S, Moskalewicz T (2016) Structure and thermal stability of Bi_3NbO_7 thin films grown by pulsed laser deposition. *Surf Coat Technol* 302:474–481. <https://doi.org/10.1016/j.surfcoat.2016.06.052>
8. Mattox DM (ed) (2018) The foundations of vacuum coating technology, 2nd edn. Elsevier, New York. <https://doi.org/10.1016/C2016-0-03988-8>. ISBN 978-0-12-813084-1
9. Papernov S, Brunsman MD, Oliver JB, Hoffman BN, Kozlov AA, Demos SG, Shvydky A, Cavalcante FHM, Yang L, Menoni CS, Roshanzadeh B, Boyd STP, Emmert LA, Rudolph W (2018) Optical properties of oxygen vacancies in HfO_2 thin films studied by absorption and luminescence spectroscopy. *Opt Express* 26:17608–17623. <https://doi.org/10.1364/OE.26.017608>
10. Zhou Y, Dong F, Jin S (eds) (2018) Bismuth—advanced applications and defects characterization. IntechOpen, Rijeka
11. Medernach JW (1975) On the structure of evaporated bismuth oxide thin films. *J Solid State Chem* 15:352–359. [https://doi.org/10.1016/0022-4596\(75\)90291-1](https://doi.org/10.1016/0022-4596(75)90291-1)
12. Condurache-Bota S, Rusu GI, Tigau N, Drasovean R, Gheorghies C (2009) Structural and optical characterization of thermally oxidized bismuth films. *Rev Roum Chim* 54:205–211
13. Condurache-Bota S, Constantinescu C, Rusu GI, Tigau N, Cantaragiu AM (2010) Oxidized bismuth films deposited by PLD with and without RF. *Ann "Dunarea de Jos" Univ Galati—Math Phys Theor Mech* 33:206–211
14. Condurache-Bota S, Rusu GI, Tigau N, Leontie L (2010) Important physical parameters of Bi_2O_3 thin films found by applying several models for optical data. *Cryst Res Technol* 45:503–511. <https://doi.org/10.1002/crat.201000074>
15. Condurache-Bota S, Tigau N, Rambu AP, Rusu GG, Rusu GI (2011) Optical and electrical properties of thermally oxidized bismuth thin films. *Appl Surf Sci* 257:10545–10550. <https://doi.org/10.1016/j.apsusc.2011.07.048>
16. Condurache-Bota S, Drasovean R, Tigau N, Rambu AP (2011) The influence of substrate temperature on the structure and on the optical reflection spectrum of bismuth thin films. *Rev Roum Chim* 56:1101–1106
17. Murariu G, Condurache-Bota S, Tigau N (2012) Polynomial fitting approach for the Kramers-Kronig method for optical properties computing for Bi_2O_3 fabric. *Int J Mod Phys B* 26:1250049. <https://doi.org/10.1142/S021797921250049X>
18. Murariu G, Condurache-Bota S (2013) Temperature dependence of the optical properties of Bi_2O_3 . A theoretical approach basing on the Kramers-Kronig transformation for polynomial mixed terms models. *Cent Eur J Phys* 11:130–137. <https://doi.org/10.2478/s11534-012-0124-x>
19. Condurache-Bota S, Praisler M, Constantinescu C, Tigau N (2014) Kramers-Kronig method applied for thin films of bismuth oxide prepared by PLD. *Ann "Dunarea de Jos" Univ Galati—Math Phys Theor Mech* 37:24–29
20. Tudorache F, Petrila I, Condurache-Bota S, Constantinescu C, Praisler M (2015) Humidity sensors applicative characteristics of granularized and porous Bi_2O_3 thin films prepared by oxygen plasma-assisted pulsed laser deposition. *Superlattices Microstruct* 77:276–285. <https://doi.org/10.1016/j.spmi.2014.11.022>
21. Condurache-Bota S, Constantinescu C, Praisler M, Tigau N (2015) The influence of the substrate temperature on the structure and on the optical energy bandgap of bismuth oxide thin films prepared by pulsed laser deposition. *Digest J Nanomater Biostruct* 10:1025–1032
22. Condurache-Bota S, Tiron V, Praisler M (2015) Highly transparent bismuth oxide thin films deposition: Morphology—Optical properties correlation studies. *J Optoelectron Adv Mater* 17:1296–1301
23. Condurache-Bota S, Constantinescu C, Tigau N, Praisler M (2016) Bismuth oxide thin films deposited on silicon through pulsed laser ablation, for infrared detectors. *Surf Rev Lett* 23:1550104. <https://doi.org/10.1142/S0218625X15501048>
24. Murariu G, Dinescu A, Murariu AG, Condurache-Bota S (2016) Comparative discussion on global models for optical properties of Bi_2O_3 . *Rom J Phys* 61:626–637
25. Hong C, Kim HW, Lee WI, Lee C (2010) $\text{Bi}_2\text{O}_3/\text{TiO}_2$ coaxial nanorods: synthesis, characterization and photoluminescence properties. *Thin Solid Films* 518:6638–6641. <https://doi.org/10.1016/j.tsf.2010.03.157>
26. Chen R, Shen ZR, Wang H, Zhou HJ, Liu YP, Ding DT, Chen TH (2011) Fabrication of mesh-like bismuth oxide single crystalline nanoflakes and their visible light photocatalytic activity. *J Alloy Compd* 509:2588–2596. <https://doi.org/10.1016/j.jallcom.2010.11.102>
27. Qiu Y, Yang M, Fan H, Zuo Y, Shao Y, Xu Y, Yang X, Yang S (2011) Phase-transitions of α - and β - Bi_2O_3 nanowires. *Mater Lett* 65:780–782. <https://doi.org/10.1016/j.matlet.2010.11.045>
28. Hou J, Yang C, Wang Z, Zhou W, Jiao S, Zhu H (2013) In situ synthesis of α - β phase heterojunction on Bi_2O_3 nanowires with exceptional visible-light photocatalytic performance. *Appl Catal B* 142–143:504–511. <https://doi.org/10.1016/j.apcatb.2013.05.050>
29. Tien LC, Lai YC (2014) Nucleation control and growth mechanism of pure α - Bi_2O_3 nanowires. *Appl Surf Sci* 290:131–136. <https://doi.org/10.1016/j.apsusc.2013.11.014>
30. Raza W, Khan A, Alam U, Muneer M, Bahnmann D (2016) Facile fabrication of visible light induced Bi_2O_3 nanorod using conventional heat treatment method. *J Mol Struct* 1107:39–46. <https://doi.org/10.1016/j.molstruc.2015.11.014>
31. Sood S, Umar A, Mehta SK, Kansal SK (2015) α - Bi_2O_3 nanorods: an efficient sunlight active photocatalyst for degradation of Rhodamine B and 2,4,6-trichlorophenol. *Ceram Int* 41:3355–3364. <https://doi.org/10.1016/j.ceramint.2014.10.038>
32. Ma XJ, Zhang WB, Kong LB, Luo YC, Kang L (2016) β - Bi_2O_3 : an underlying negative electrode material obeyed electrode potential over electrochemical energy storage device. *Electrochim Acta* 192:45–51. <https://doi.org/10.1016/j.electacta.2016.01.154>
33. Deepi A, Srikanth G, Samson Nesaraj A (2018) Electrochemical performance of Bi_2O_3 decorated graphene nano composites for supercapacitor applications. *Nano-Structures & Nano-Objects* 15:10–16. <https://doi.org/10.1016/j.nanos.2018.03.003>
34. Guo X, Liang TT, Rager M, Cui X (2018) Low-temperature controlled synthesis of novel bismuth oxide (Bi_2O_3) with microrods and microflowers with great photocatalytic activities. *Mater Lett* 228:427–430. <https://doi.org/10.1016/j.matlet.2018.06.058>
35. Qiu Y, Fan H, Chang X, Dang H, Luo Q, Cheng Z (2018) Novel ultrathin Bi_2O_3 nanowires for supercapacitor electrode materials with high performance. *Appl Surf Sci* 434:16–20. <https://doi.org/10.1016/j.apsusc.2017.10.171>
36. Jung HJ, Park S, Kim KD, Kim TH, Choi MY, Lee KY (2018) Fabrication of porous β - Bi_2O_3 nanoplates by phase transformation of bismuth precursor via low-temperature thermal decomposition process and their enhanced photocatalytic activity. *Colloids Surf A* 550:37–45. <https://doi.org/10.1016/j.colsurfa.2018.04.034>
37. Viruthagiri G, Kannan P (2019) Visible light mediated photocatalytic activity of cobalt doped Bi_2O_3 nanoparticles. *Journal of Materials Research and Technology* 8:127–133. <https://doi.org/10.1016/j.jmrt.2017.06.011>
38. Leontie L, Caraman M, Visinoiu A, Rusu GI (2005) On the optical properties of bismuth oxide thin films prepared by pulsed

- laser deposition. *Thin Solid Films* 473:230–235. <https://doi.org/10.1016/j.tsf.2004.07.061>
39. Fan HT, Pan SS, Teng XM, Ye C, Li GH, Zhang LD (2006) δ - Bi_2O_3 thin films prepared by reactive sputtering: fabrication and characterization. *Thin Solid Films* 513(2006):142–147. <https://doi.org/10.1016/j.tsf.2006.01.074>
 40. Gomez CL, Depablos-Rivera O, Silva-Bermudez P, Muhl S, Zeinert A, Lejeune M, Charvet S, Barroy P, Camps E, Rodil SE (2015) Opto-electronic properties of bismuth oxide films presenting different crystallographic phases. *Thin Solid Films* 578:103–112. <https://doi.org/10.1016/j.tsf.2015.02.020>
 41. Condurache-Bota S, Tigau N, Praisler M, Prodan G, Gavrila R (2017) Near-infrared energy bandgap bismuth oxide thin films and their in-depth morpho-structural and optical analysis. *Rom Rep Phys* 69:507
 42. Yakuphanoglu F, Durmus M, Okutan M, Köysal O, Ahsen V (2006) The refractive index dispersion and the optical constants of liquid crystal metal-free and nickel(II) phthalocyanines. *Phys B* 373:262–266. <https://doi.org/10.1016/j.physb.2005.11.153>
 43. He C, Xu F, Wang J, Liu Y (2009) Refractive index dispersion of relaxor ferroelectric $0.9\text{Pb}(\text{Zn}_{1/3}\text{Nb}_{2/3})\text{O}_3$ — 0.1PbTiO_3 single crystal. *Cryst Res Technol* 44:211–214. <https://doi.org/10.1002/crat.200800385>
 44. JCPDS data file numbers: 01-0688, 05-0519, 18-244, 27-49, 27-50, 27-51, 27-52, 27-54, 29-236, 41-1449, 44-1246, 45-1344, 47-1057, 47-1058, 71-0465, 71-0466, 71-0467, 71-2274, 72-0398, 74-1373, 74-1375, 74-1633, 74-1999, 74-2352, 75-0993, 75-0995, 76-1730, 77-0374, 77-0868, 77-2008, 78-0736, 81-0563, 83-0410, 85-1329
 45. Condurache-Bota S, Constantinescu C, Praisler M, Gavrila R, Tigau N, Gheorghies C (2014) Influence of the preparation method on the morpho-structural and optical properties of bismuth oxide thin films. *International semiconductor conference/ CAS proceedings*. pp 69–72, IEEE Catalog Number: CFP14CAS-PRT; ISBN: 978-1-4799-3916-9; ISSN: 1545-827X
 46. Hincapié CMB, Cárdenas MJP, Orjuela JEA, Parra ER, Florez JJO (2012) Physical-chemical properties of bismuth and bismuth oxides: synthesis, characterization and applications. *Dyna* 176:139–148
 47. Gujar TP, Shinde VR, Lokhande CD (2008) The influence of oxidation temperature on structural, optical and electrical properties of thermally oxidized bismuth oxide films. *Appl Surf Sci* 254:4186–4490. <https://doi.org/10.1016/j.apsusc.2008.01.040>
 48. Koinkar VN, Bhushan B (1997) Effect of scan size and surface roughness on microscale friction measurements. *J Appl Phys* 81:2472. <https://doi.org/10.1063/1.363954>
 49. Bellitto V (ed) (2010) Atomic force microscopy—imaging, measuring and manipulating surfaces at the atomic scale. InTechOpen, Rijeka. <https://doi.org/10.5772/2673>. ISBN 978-953-51-0414-8
 50. Kumar BR, Rao TS (2012) AFM studies on surface morphology, topography and texture of nanostructured zinc aluminum oxide thin films. *Dig J Nanomater Biostruct* 7:1881–1889
 51. Miller JD, Veeramasuneni S, Drelich J, Yalamanchili MR, Yamauchi G (1996) Effect of roughness as determined by atomic force microscopy on the wetting properties of PTFE thin films. *Polym Eng Sci* 36:1849–1855. <https://doi.org/10.1002/pen.10580>
 52. Rusu RS, Rusu GI (2005) On the electrical and optical characteristics of CdO thin films. *J Optoelectron Adv Mater* 7:1511–1516
 53. Iljinas A, Burinskas S, Dudonis J (2011) Synthesis of bismuth oxide thin films deposited by reactive magnetron sputtering. *Acta Phys Pol A* 120:60–62. <https://doi.org/10.12693/APhysPolA.120.60>
 54. Dabbabi S, Ben Nasr T, Ammar S, Kamoun N (2018) Synthesis and characterization of zinc-tin-mixed oxides thin films. *Superlattices Microstruct* 123:129–137. <https://doi.org/10.1016/j.spmi.2018.05.058>
 55. Gowthami V, Meenakshi M, Perumal P, Sivakumar R, Sanjeeviraja C (2014) Optical dispersion characterization of NiO thin films prepared by nebulized spray technique. *Int J ChemTech Res* 6:5196–5202
 56. Oriaku CI, Osuwa JC (2009) On the optical dispersion parameters of thin film Al^{3+} doped ZnO transparent conducting glasses. *J Ovonic Res* 5:213–218

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