Research article

Ni doping induced property enhancement in laser ablated BaSnO$_3$ films suitable for optoelectronic applications

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A R T I C L E   I N F O

A B S T R A C T

Pulsed laser deposition is a straightforward approach for preparing films with superconducting to dielectric properties with atomic layer precision. The deep-seated mechanisms involved in the particle transport from target to substrate and subsequent film formation still need to be fully comprehended. This manuscript reports the property enhancement observed in laser ablated perovskite BaSnO$_3$ films with Ni doping. Films' crystallinity improvement is observed, and an intensity enhancement of 1150% is observed on 3 mol% Ni-doping. The optimum Ni-doping concentration in BaSnO$_3$ is found to be 3 mol%. Herein, Ni-doped BaSnO$_3$ films deposited by PLD showed an unusual increase in film thickness (i.e., from 615 nm in the pure film to 1317 nm in the film with 7 mol% Ni-doping as revealed by lateral SEM analysis and spectroscopic ellipsometry). We propose an "Induced Magnetic field-assisted Particle Convergence (IMPC)" effect for this superficial growth enhancement. The film's optical properties are modified with an increased nickel doping level, and the bandgap energy shows renormalization. All the films show excellent transmittance (80–90%) in the Vis.-NIR region. Hall-effect measurement reveals the increased carrier concentration by three orders (2.98×10^{11} to 3.50×10^{14} cm^{-3}). In addition, the enhancement in mobility from 3.13 to 20.93 cm^{2}V^{-1}s^{-1} and a decrease in electrical resistivity by six orders (i.e., from 4.05×10^9 to 1.13×10^3 Ω cm) are observed on 7 mol% Ni doping. XPS measurements reveals that the Ba, Sn and Ni ions are at 2+, 4+ and 2+ oxidation states. Using spectroscopic ellipsometric method, we estimated the optical constants of the films, the refractive index, dielectric constant, and extinction coefficient show a normal dispersion behavior. The high crystallinity, high transmittance, suitable surface topography, and improved electrical performances of the Ni-doped BaSnO$_3$ films make them excellent candidates for optoelectronic devices and solar cells.

1. Introduction

BaSnO$_3$, having an ABO$_3$ structure where Ca, Sr, or Ba at site A and a transition metal at site B, belongs to the perovskite oxide family [1]. Perovskite oxide films are gaining much attention as a TCO because of their physical properties [1–3]. BaSnO$_3$ is a (n-type)

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wide bandgap semiconductor ($E_g = 3.1$ eV) with a cubic perovskite structure [4,5]. Various ways to prepare BaSnO$_3$ have been reported [6,7]. With the proper substitution at Ba and Sn cation sites, the film properties of BaSnO$_3$ can be modified [8]. The pure and doped forms of BaSnO$_3$ find an essential application in thermally stable and ceramic boundary layer capacitors [9]. It can be used as a sensor material for gases such as CO, NO, and Cl and humidity sensors [6–10]. The properties of perovskite oxides get altered or modulated by doping, and new exciting features are obtained by elemental substitution of transition elements.

Upadhyay et al. reported nickel doping in BaSnO$_3$ by the self-combustion method and investigated it for humidity-sensing application [10]. In BaSnO$_3$, nickel can be substituted in both Ba and Sn sites. Upendra Kumar et al. reported that nickel-doped BaSnO$_3$ is useful in spintronic device applications [11]. Kumar et al. observed decreased crystallite size and lattice strain in Ni-doped BaTiO$_3$ films without undergoing any crystal structure phase change [12]. BaSn$_{(1-x)}$Y$_x$O$_{3-\delta}$ compounds showed a p-type and ionic behavior in an oxidative and slightly reducing ambiance [13]. Y-doped BaSnO$_3$ with ZnO additive shows a perovskite cubic single phase and can have potential applications for fuel cell technologies [14]. Liu et al., while doping Sb in BaSnO$_3$, observed a reduced optical transmittance and a subsequent widening of bandgap energy in BaSnO$_3$. These films exhibit a resistivity of 2.43 mΩcm, mobility of 1.75 cm^{2}V^{-1}s^{-1}, and carrier concentration of 1.65×10^{21} cm^{-3} [15]. Anoop et al. deposited La-doped BaSnO$_3$ epitaxial films (substrate-SrTiO$_3$) by PLD and observed that Sn^{2+} defects produced on vacuum-annealing can control their electrical properties [16]. Laser-ablated Fe-doped BaSnO$_3$ films on SrTiO$_3$ substrates under an oxygen partial pressure of 300 mTorr show a highly crystalline nature [17]. Shahid et al. reported the crystal structure of sol-gel prepared Ni-doped BaSrTiO$_3$ films [18]. Singh et al. observed a strong volumetric strain dependence on the bandgap and the index of refraction in BaSnO$_3$ films [19]. Sumitra et al. [20] investigated the optical bandgap tuning of Co-doped BaSnO$_3$ nanostructures. Sharma et al. [21] found that Ni-doped (5 wt%) BiFeO$_3$ film increases bandgap energy from 2.85 to 3.18 eV. Gao et al. [22] fabricated Co: BaSnO$_3$ films (substrate- MgO) by PLD and observed that the bandgap energy increases first and then decreases with doping concentration increases. Zhang et al. [23] deposited Cr-doped BaSnO$_3$ films (substrate- F-doped SnO$_2$) with the colloidal solution approach. They found that the deposited nanoporous perovskite structures have tunable bandgap energy and have various applications in photoelectric devices. Our previous investigations reported the nonlinear optical and magnetic properties of Ni-doped, Mn-doped, and Fe-doped BaSnO$_3$ powder samples [24–26]. Further, the supercapacitor behavior of Mn-doped BaSnO$_3$ powders is also reported [25]. We expect the modified optical and electrical properties of BaSnO$_3$ by Ni-doping. Ni^{2+} ions when substituted for Sn^{4+} ions in the host lattice we can expect an enhancement in the properties of doped BaSnO$_3$. Also, Ni can introduce shallow energy levels in the forbidden energy gap region, which can modify the material's bandgap. Considering these aspects, we have selected Ni as a dopant for the present study.

Because of its versatile and flexible physical vapor phase, Pulsed Laser Deposition (PLD) is one of the best techniques to obtain high-quality pure and doped BaSnO$_3$ films. This manuscript reports the deposition of pure and Ni-doped BaSnO$_3$ films (substrate-quartz) by
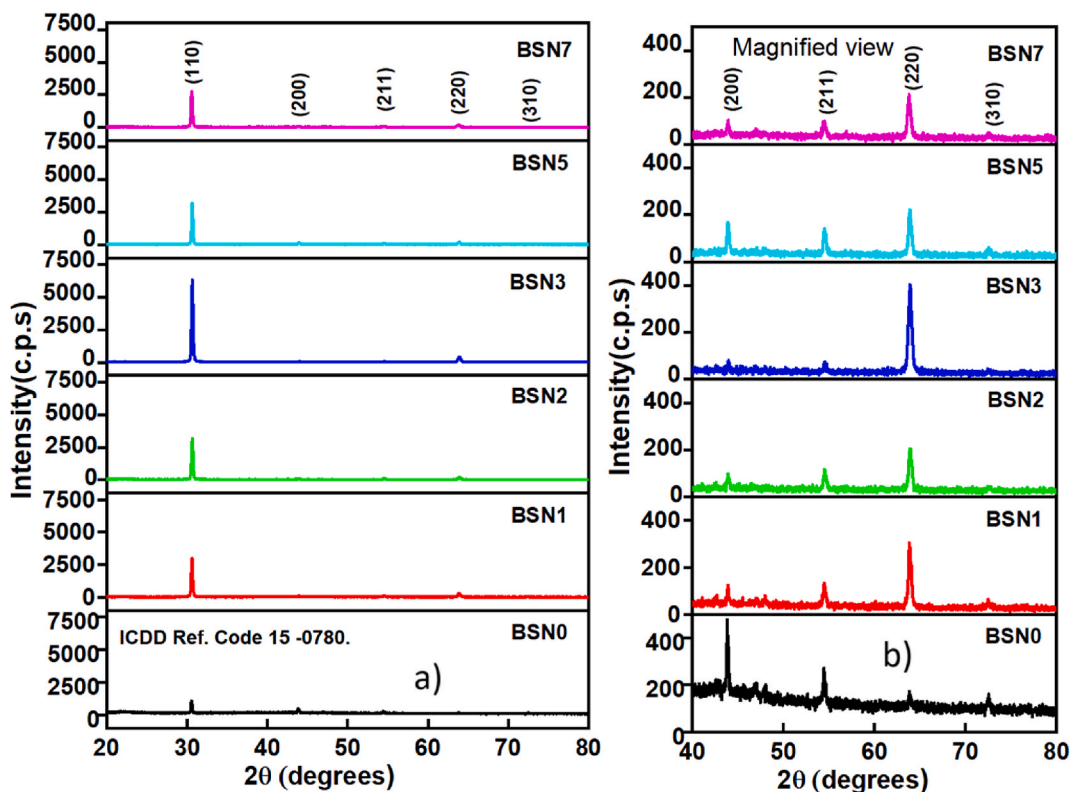

Fig. 1. a) XRD patterns of BaSnO$_3$ films with different Ni doping levels, and b) magnified view of the selected region to display less intense peaks.

PLD and the investigation of the impact of Ni-doping on their various properties.

2. Materials and methods

The BaSnO$_3$ and Ni-doped BaSnO$_3$ powders were prepared using a solid-state ceramic approach. We prepare the pellets by mixing the high-purity BaCO$_3$, SnO$_2$, and NiO powders with acetone for 6 h and heating at 1250 °C for 6 h. The prepared pellets were sintered at 1000 °C for 6 h and used as the target material. The pure and Ni-doped BaSnO$_3$ films are laser deposited as explained in our earlier studies [27,28] with the following deposition parameters viz. substrate-quartz, duration- 45 min, laser energy - 60 mJ, oxygen pressure - 0.02 mbar, the temperature on the substrate - 600 °C, annealing - 900 °C). The BaSnO$_3$ films with 0, 1, 2, 3, 5, and 7 mol% Ni doping are termed BSN0, BSN1, BSN2, BSN3, BSN5, and BSN7 respectively. The Ni-doped BaSnO$_3$ films were investigated for their structural, optical, morphological, and electrical properties in detail (see the supplementary Information for description).

3. Results and analysis

XRD data (Fig. 1) of BaSnO$_3$ films doped with different nickel concentrations ($x = 0, 1, 2, 3, 5,$ and 7 mol%) show the polycrystalline nature with cubic phase (ICDD Ref. Code 15–0780) [12,23]. The BSN0 film shows two strong peaks for 2θ values at 30.61° and 43.98° and three less intense peaks at 54.72, 63.84, and 72.64° and they correspond respectively to (110), (200), (211), (220) and (310) planes of BaSnO$_3$ cubic phase. The highest intensity of the (110) peak suggests that (110) is the preferred growth orientation in the BSN0 film. The (110) peak intensity increases with the enhancement in Ni doping level up to 3 mol% and shows a slight decrease afterward. In all the Ni-doped films, <110> remains the preferred crystal growth direction. The (110) peak intensity for the films with Ni doping, viz., 1, 2, 3, 5, &7 mol %, are respectively 5.5, 5.8, 11.5, 6, and 5.1 times that of BSN0. This enormous increase in intensity with Ni doping suggests the improvement of crystallinity with Ni doping and indicates that the dopant Ni atoms act as new centers of crystal growth. For the BSN0, the I$_{200}$/I$_{220}$ intensity ratio is 0.217. Ni doping, shows a shift in the intensity from the (200) to (220) peak. The relative (220) peak intensity to that of (200) in the films with 1, 2, 3, 5, & 7 mol %, Ni doping levels are respectively 2.00, 2.61, 8.58, 5.53, and 5.5 [Fig. S 1(a), supplementary Information], and this suggests the promotion of crystal growth along <110> direction by the dopant Ni atom.

The Ni-doped films show no additional peaks other than BaSnO$_3$ in the XRD pattern. The BSN0 film shows a FWHM (β$_{110}$) of 0.22° for the (110) peak. The Ni-doped films show less β$_{110}$ value as compared to that of BSN0 film. The reduction in β$_{110}$ value with Ni doping also suggests the improvement of crystallinity. The β$_{(110)}$ also shows an initial decrease with Ni doping up to 3 mol% and increases then [Fig. S1(b), supplementary information]. The maximum intensity and the lowest FWHM value of the most preferred orientation (110) plane for the BSN3 film indicate its highest crystalline quality. The defects and disorders introduced in the films on heavy doping can be the reason for the slight reduction in crystallinity observed in the films with higher doping levels. Thus, 3 mol % is the optimum doping level for Ni in BaSnO$_3$ film. The improvement in crystallinity observed in the Ni-doped films can also attributed to the enhanced value of thickness (as revealed by the vertical SEM analysis and spectroscopic ellipsometric analysis). The heavy-doped films show higher thickness values than that for low or moderate doping. However, the films with rich doping exhibit a slight reduction in crystalline quality compared to that of the BSN3 film. The tendency to reduce crystallinity due to the formation of defects and disorder on heavy doping nullifies the propensity to improve crystallinity due to the enhancement in thickness in highly Ni-doped films.

The position of the most intense (110) peak shifts systematically towards a higher 2θ value, with Ni doping concentration enhanced [Fig. S1(c), supplementary Information]. The ionic radii of Ni^{2+} is 0.63 Å, and that of Ni^{3+} is 0.56 Å, and are lesser than the ionic radius of Sn^{4+} = 0.69 Å [12,29]. Thus, Ni can easily occupy the site of Sn. Since the ionic radii of Ni ions are less than that of the Sn^{4+} ions, the substitution of Ni ions in the Sn^{4+} site results in the contraction of the lattice and can lead to tensile stress in the films. The observed shift of 110 peak towards the higher 2θ range with Ni doping can be due to Ni substitution. The observed systematic reduction in lattice

Table 1
Structural parameters of BaSnO$_3$ films.

Sample code	β$_{(110)}$ (°)	Crystallite size (nm)		Lattice strain	Lattice constant (nm)	RMS surface roughness (nm)	Thickness (nm)	
		Scherer Equation	WH plot				FESEM	Ellipsometric analysis
BSN0	0.220	35	56 ± 15	0.0027 ± 0.0007	4.126	4.21	615	606.12 ± 0.7
BSN1	0.219	36	62 ± 13	0.0036 ± 0.0014	4.125	10.94	712	704.15 ± 0.26
BSN2	0.210	38	74 ± 16	0.0048 ± 0.0006	4.120	10.38	771	760.23 ± 0.46
BSN3	0.209	39	85 ± 10	0.0048 ± 0.0018	4.118	2.33	1240	1210 ± 0.49
BSN5	0.211	37	76 ± 7	0.0076 ± 0.0001	4.117	3.77	1306	1291 ± 0.78
BSN7	0.218	36	79 ± 11	0.0055 ± 0.0005	4.116	8.32	1317	1303 ± 1.3

constant with Ni doping enhancement [Fig. S1(d), supplementary information, and Table 1] indicate lattice contraction due to Ni doping.

We used the Scherrer formula to calculate the crystallite size (Table 1) [30]. The crystallite size of the films is also estimated (Table 1) using the Williamson–Hall (W–H) relation [Fig. S2 supplementary information] [30], which is higher than that obtained from Scherer formulae, indicating the broadening of peaks due to strain. The strain value for BSN0 is less than those estimated for doped films.

FESEM images (Fig. 2) give the surface topography of the BaSnO$_3$ films. The growth mechanism exhibited by BaSnO$_3$ film is the Stranski–Krastnov intermediate growth [27]. Initially, a layer-by-layer (Frank–Van der Merwe) deposition occurs. The growth mechanism changes to the Volmer–Weber 3D island growth due to the enhanced elastic strain energy when the film thickness is large [28]. The FESEM image of BSN0 presents a continuous film with regular distinct islands, which confirms the Stranski–Krastnov intermediate growth mechanism. The surface morphology of BSN1 shows a similar pattern but with a more significant number of such discrete islands, and this number increases with nickel doping concentration enhancement up to 3 mol%. The BSN3 film shows a dense distribution of such distinct islands with clear grain boundaries. The microstructure of BSN3 presents grains of larger size which are in highly ordered orientation and this can be one of the reason for its superior crystalline quality. The FESEM image of BSN7 presents a
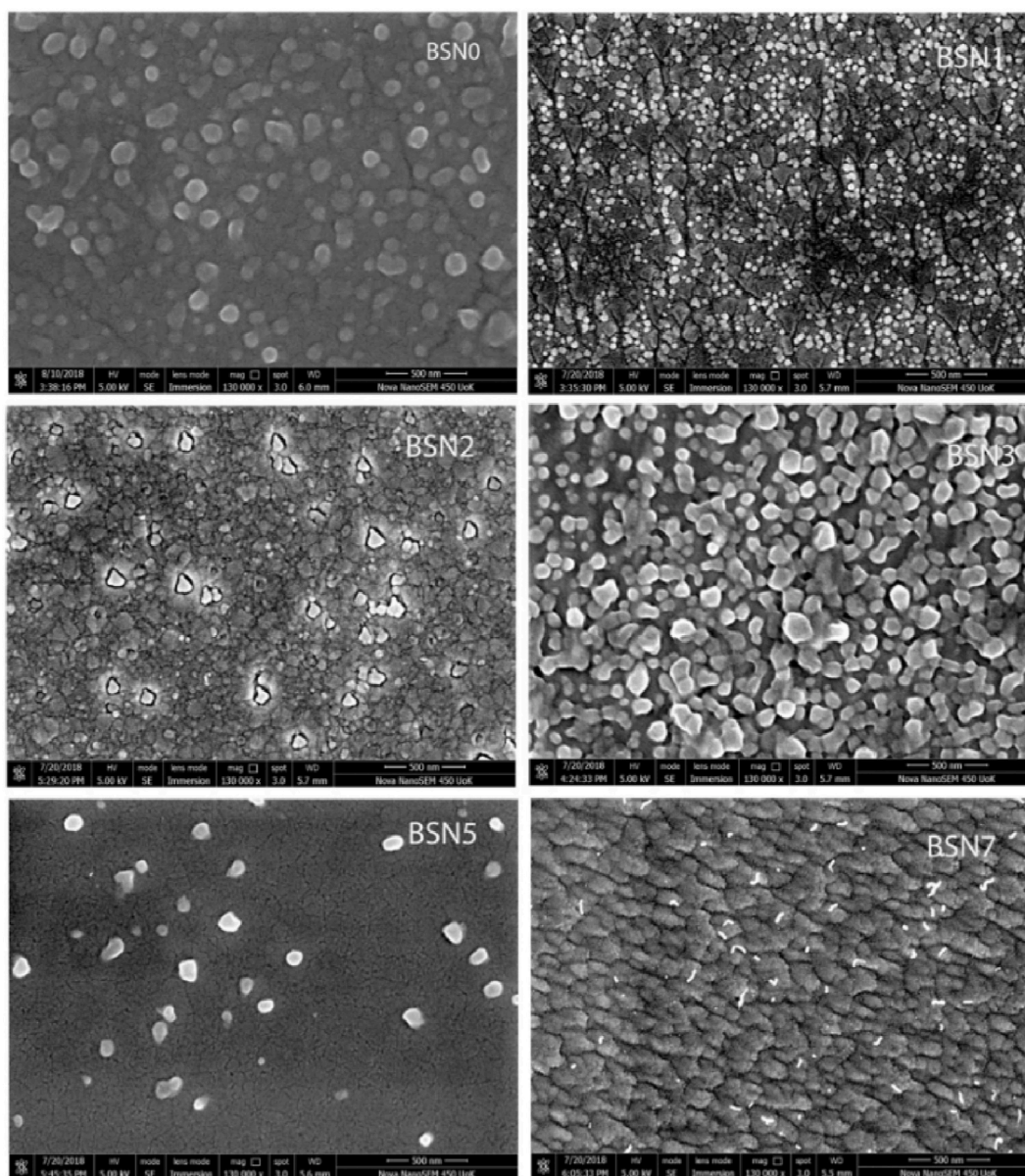

Fig. 2. FESEM images of Ni doped BaSnO$_3$ films.

dense distribution of well-aligned separate islands with clear grain boundaries. The microstructure of all films have a smooth pinhole free surface suitable for optoelectronic applications.

The EDS spectra confirms nickel presence in BaSnO$_3$ films (Fig. 3). The elemental composition estimated from EDX analysis is shown in Fig. 3(e). The Ni concentration calculated from the films are slightly lesser than that in the PLD target. But it shows a linear relationship with that in the PLD target (Fig. 3(f)).

Fig. 4 presents the lateral SEM micrographs of BaSnO$_3$ films, and we estimated the film thickness from them. We observed that the film thickness enhanced regularly with a dopant level increase. Table 1 gives the estimated film thickness of BaSnO$_3$ films, and the thickness variation with Ni doping is plotted (Fig. 5). Interestingly, a remarkable hike in thickness from ~615 nm in BSN0 film to ~1317 nm in BSN7 film was observed. Hence, we also carried out the film thickness estimation using the ellipsometric measurements with a three-layer model and the fitment of data acquired with a low $\chi 2$ value. The ellipsometric analysis also presents a similar trend in thickness variation (606.12 ± 0.7 nm for BSN0 and 1303 ± 1.3 nm for BSN7) (Table 1 and Fig. 5). The only other factor that can stimulate the film growth is the presence of Ni in the plasma generated and subsequent plasma expansion and transport.

In the PLD method, the laser radiation is focused on the target surface. The laser light ablates the target material and creates a plasma plume. The huge temperature difference between the point of plasma generation and the surroundings paves the way for an adiabatic expansion of the plume. This adiabatic expansion guides the particles to move in a direction perpendicular to the target surface. Thin film condensed on a substrate from the ablated species placed at an angle opposite to the target. A stoichiometric transfer
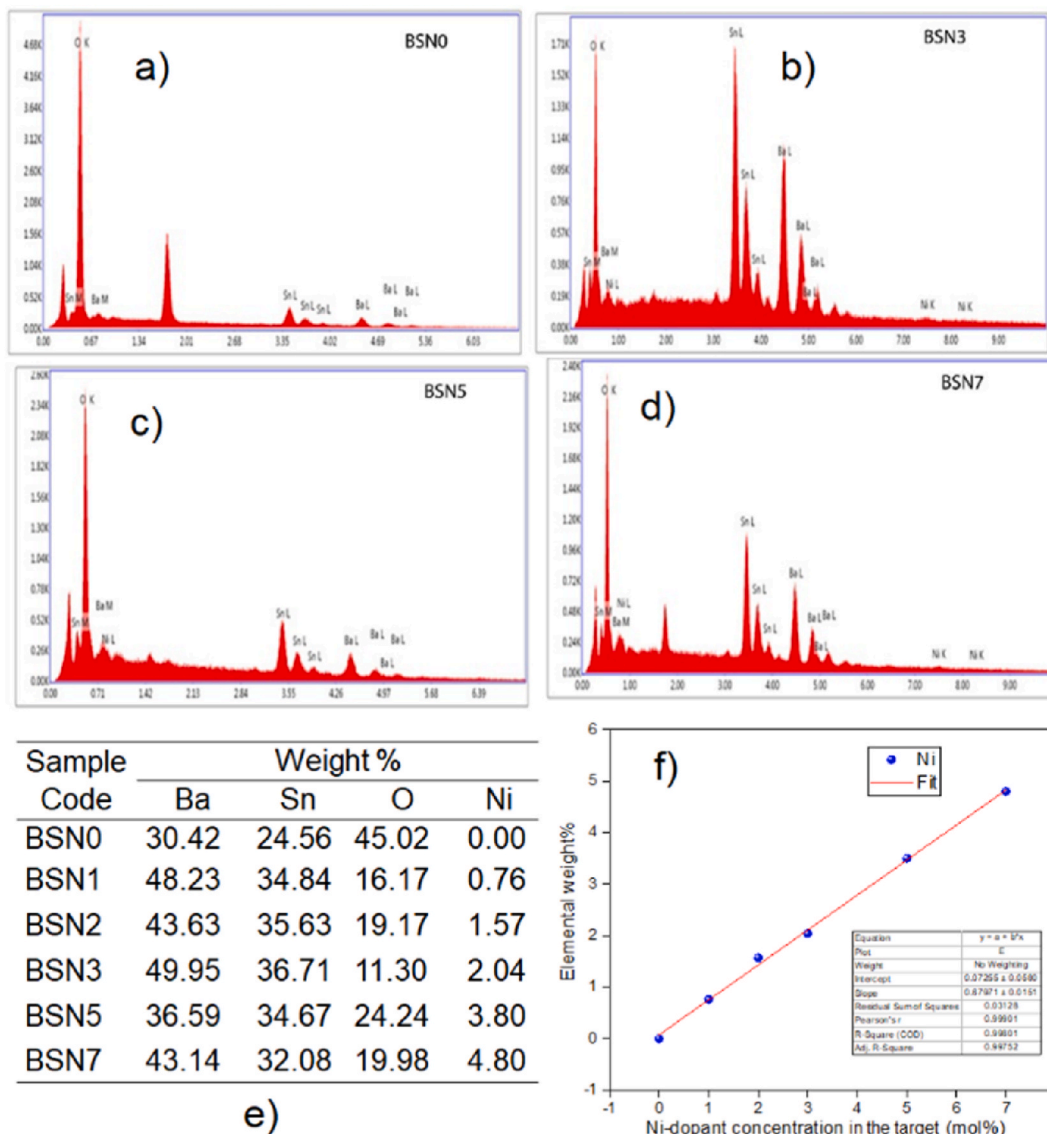

Fig. 3. (a to d) EDX spectra of selected Ni doped BaSnO$_3$ films, e) elemental composition in different films, f) plot of Ni concentration wt% in the films vs. Ni-dopant concentration in the PLD target.
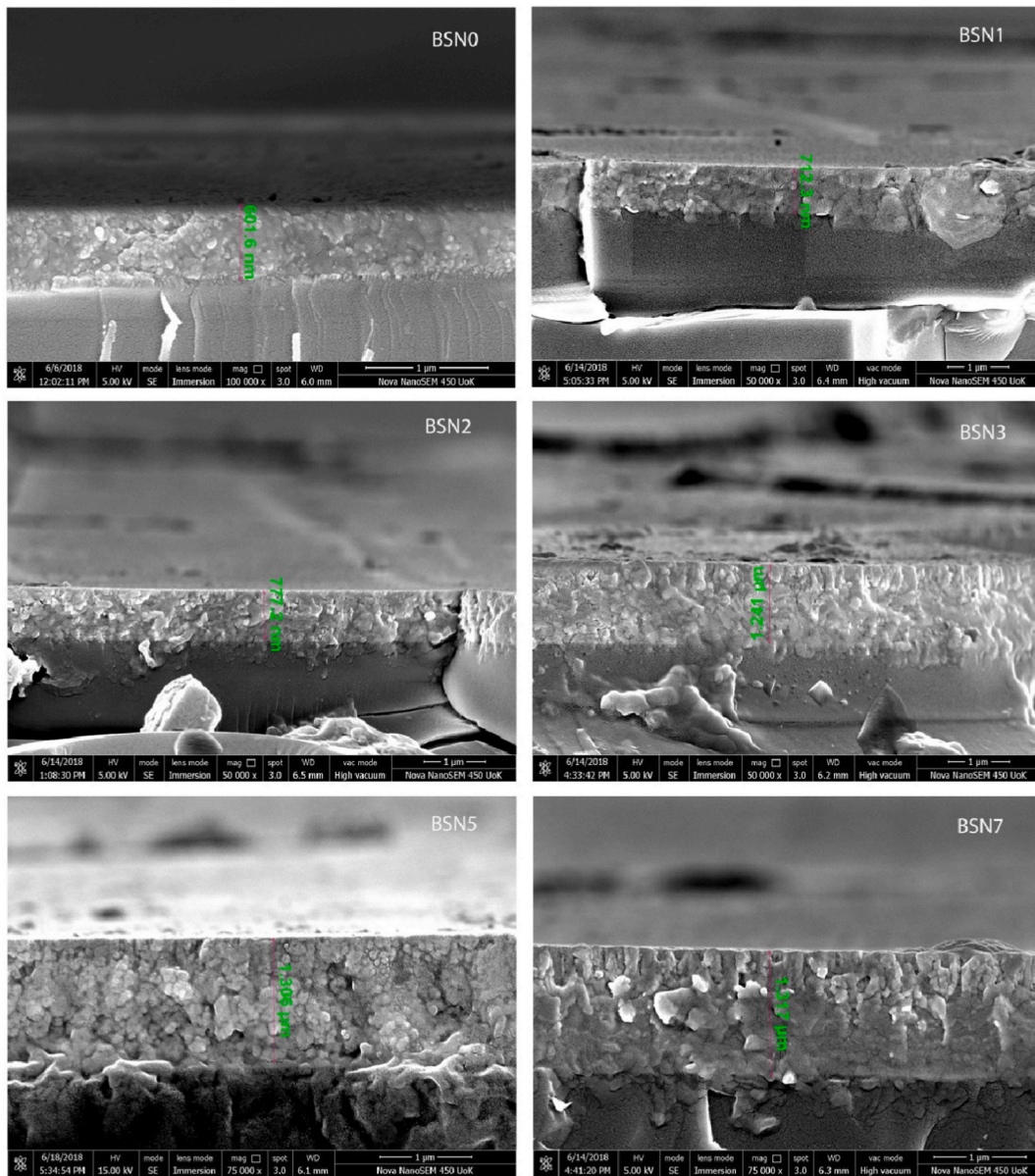
Fig. 4. Lateral FESEM images of pure and Ni:BaSnO$_3$ films.

of ablated material from the target occurs, and the background gas sufficiently provides the anions. In the laser ablation method, each laser pulse generated will give material sufficient for the desired phase of sub-monolayer for the deposition [31]. The film growth rate per laser pulse will depend on background gas pressure, target–substrate separation, laser energy fluence, and laser spot size [32]. In the present case, all the deposition parameters, such as background oxygen pressure, substrate nature and temperature, target–substrate separation, deposition duration, laser wavelength, spot size, and laser fluence, remain the same during deposition. To our surprise, the literature shows no report of such observation.

PLD Aurora method explains the enhancement of film deposition rate with increasing applied magnetic field [33]. It describes an enhanced ionization of the ablated particles during transport from the target to substrate through interaction between the particles and applied magnetic field by using a permanent magnet or an electromagnet in the setup. It is to be worth mentioning that, we do not apply any magnetic field externally during deposition. Hence, the observed increase in thickness cannot be attributed to Aurora PLD. Because of that, we propose a growth mechanism, the Induced Magnetic field-assisted Particle Convergence (IMPC) effect, to explain this unusual yet exciting observation.

The laser ablation generates a plasma plume at the target surface, and it may contain BaSnO$_{3-x}$, Ba$^+$, Sn$^+$, NiO$_{1-x}$, Ni$^+$, and electrons. The adiabatic expansion of the plume rapidly removes these entities from the target surface and surges, usually outwards to the surface. The kinetic energy acquired by heavily positive ions and electrons will differ; hence, we can expect a net displacement
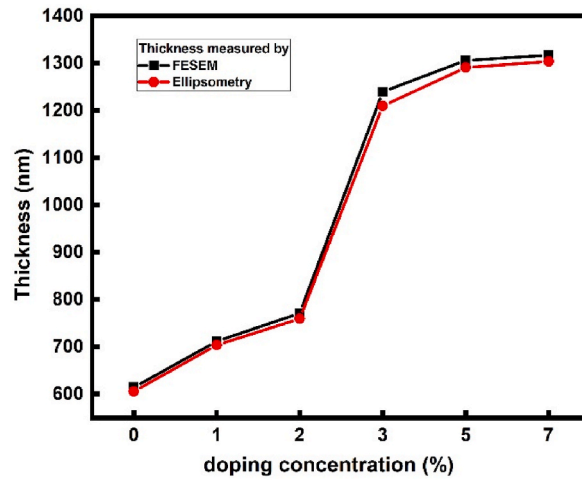
Fig. 5. The plot shows the thickness variation as a function of Ni doping concentration.

between them, leading to a net electric field pointing toward the target. The adiabatic expansion cools the temperature inside the plume, and the nickel nanoparticles may get magnetized due to the fostered electric field. Reports show that the oxygen-deficient $BaSnO_3$ ions are paramagnetic [12,34,35]. The induced magnetic field around the nickel can attract the otherwise diverging $BaSnO_{3-x}$ ions (having a paramagnetic nature) toward it, leading to a convergence effect of $BaSnO_{3-x}$ particles towards regions with higher concentrations of nickel particles within the plume. Hence, the film thickness can increase with nickel incorporation because of this
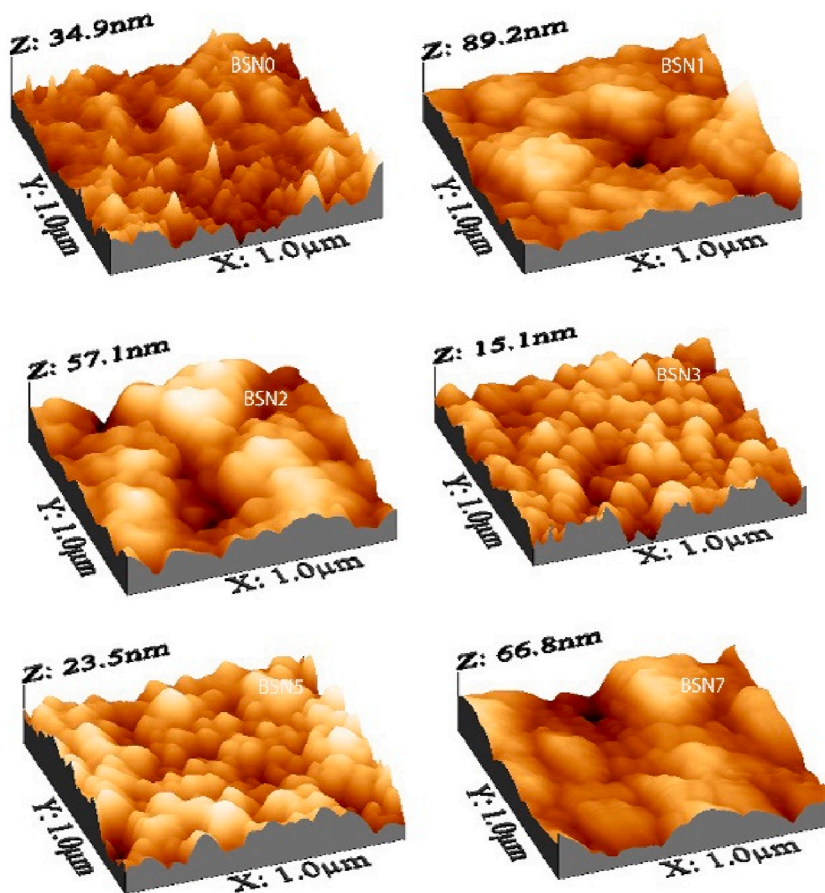
Fig. 6. AFM images of Ni-doped $BaSnO_3$ films.

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(separation = 8.3 eV) at 486.3 eV and 494.6 eV, respectively, confirming the Sn^{4+} state.

Fig. 7(c) gives the core level spectrum of oxygen in BSN3 film. The O1s peak in the BSN3 film is de-convoluted into three peaks at 530.1, 531.8, and 535 eV due to lattice oxygen atoms in the perovskite structure, oxygen vacancy in the $BaSnO_3$ and chemisorbed oxygen in hydroxyl form respectively. The fitted and de-convoluted Ni spectrum (Fig. 7(d)) shows two peaks at 855.4 eV and 872.8 eV due to the Ni $^2p_{3/2}$ and Ni $^2p_{1/2}$ states, respectively. The binding energy difference between these doublet peaks is 17.4 eV, corresponding to the Ni $^{2+}$ state [46,47].

Table 2 presents the transmittance values of the films averaged over 400–2300 nm range from the transmittance data (Fig. 8). The pure film is transparent with a light grey color. However, the film's color gradually changes to dark brown with dopant level enhancement. The excellent transmittance (80–90 %) exhibited by all films indicates their good optical quality. XRD analysis also shows excellent crystalline quality for all the films. The SEM and AFM analysis suggest a smooth and uniform surface morphology for them. The observed high value of transmittance can be due to these reasons. BSN0 film shows the highest average transmittance value (90 %) among the films. From Table 2, we can see a systematic decrease in transmittance with increased Ni doping level. Surface morphology, crystallinity, thickness, strain, and defects can affect transmittance values. In the present case, we have observed that the thickness of films shows an enormous enhancement with dopant level increase. We can attribute the observed transmittance decrease in the doped films with Ni doping concentration enhancement to the enhancement in film thickness on Ni doping.

The thickness values for BSN0 and BSN7 films are 615 nm and 1317 nm, (lateral SEM data) respectively. Though there is a steep increase in film thickness with the dopant level increase, the decline in transmittance with the dopant increase is not that much. BSN7 film possesses 80% transmittance. The SEM and AFM analysis suggests a good surface feature for films. The very high crystalline quality and better surface morphology of the Ni-doped films might have reduced the effect of increased thickness on transmittance. High transparency observed for the films in the visible and infrared regions suggests their suitability for optoelectronic applications.

The bandgap energy (E_g) estimated [48,49] for the BSN0 film is 3.15 eV. The E_g value decreases regularly with increased Ni doping (Table 2). M. Khalfallah et al. observed a similar effect of bandgap narrowing in Ni-doped SnO_2 films [50]. The energy difference between the edges of the valence band (VB) and the conduction band (CB) gives the optical bandgap [51]. The O 2p orbitals constitute the top of VB, whereas the 5s orbitals of Sn form the bottom of CB [52]. The enormous dispersion among the intra-energy levels on Ni doping replaces the Sn^{4+} site in $BaSnO_3$; hence, the density of states in VB increases, creating intermittent states in the bandgap [53]. This bandgap energy renormalization with Ni doping can have various photoelectric applications.

We employ the spectroscopic ellipsometry technique for measuring the optical parameters [Fig. S4, supplementary information]. A three-layer model having the quartz substrate as the bottom layer, $BaSnO_3$:Ni as the intermediate layer, and the $BaSnO_3$:Ni plus voids in the top layer, and DELTAPSI2TM software was used for the optical modeling and analysis [54]. We used the Lorentz oscillator model for the analysis. We also estimated the film thickness with this technique, and the estimated values agree well with those obtained from the cross-sectional SEM analysis (Fig. 5). Cherrad et al. observed that the static index of refraction (n) of $BaSnO_3$ at the equilibrium constant is 2.07, which increased with photon energy [55]. We observed that n decreases systematically with wavelength, which shows normal dispersion behavior for all the films' (Fig. 9(a))

The film's extinction coefficient K also showed a behavior similar to n (Fig. 9(b)). The low value of K indicates that the optical losses due to absorption are minimal for films supporting their high transparency. The dielectric constant gives information about the reflection and loss of light when light propagates through the film [56]. The dielectric constant (both real and imaginary components ε_r and ε_i) follows a similar variation behavior with wavelength as described by n and K (Fig. 9(c and d)).

PL spectra (at excitation at 350 nm) of $BaSnO_3$ films show emissions extending from the near UV to the visible region with emission peaks at 385, 450, 480, and 580 nm for all the films (Fig. 10). The allowed transition from O2p to Sn5s energy levels appears at 390 nm [20]. The 450 nm emission is assigned to the charge transfer within the SnO_6 octahedra [57]. The emissions at 480 and 580 nm are due to $^3P_1-^1D_2$ and $^2D_{5/2}-^2F_{7/2}^0$ transitions of Sn [58,59]. In metal oxides, the substitution or doping of transition metal ions will cause defects due to charge compensation [60]. Both anionic and cationic vacancies are available in perovskites, and hence, this behavior can be expected [57,61]. PL peaks show no shift in position with Ni doping, but the PL intensity shows slight variations with Ni doping concentration.

Table 3 shows the electrical parameters obtained from the Hall Effect measurements. The carrier concentration obtained for BSN0 film is 2.98×10^{11} cm^{-3}. It shows a systematic increase with Ni doping level enhancement, owing to improved crystallinity of the films. Ni doping increases the carrier mobility (Table 3), and the carrier mobility increases (by three orders) from 3.13 cm^{2}V^{-1}s^{-1} in BSN0 to 20.93 cm^{2}V^{-1}s^{-1} in BSN7 film. The film's electrical resistivity decreases systematically with the Ni doping level enhancement. The electrical resistivity values for BSN0 and BSN7 films are 4.05×10^9 Ωcm and 1.13×10^3 Ωcm, respectively, and thus, the enhancement

Table 2

Optical parameters of Laser ablated $BaSnO_3$ film calculated using ellipsometry.

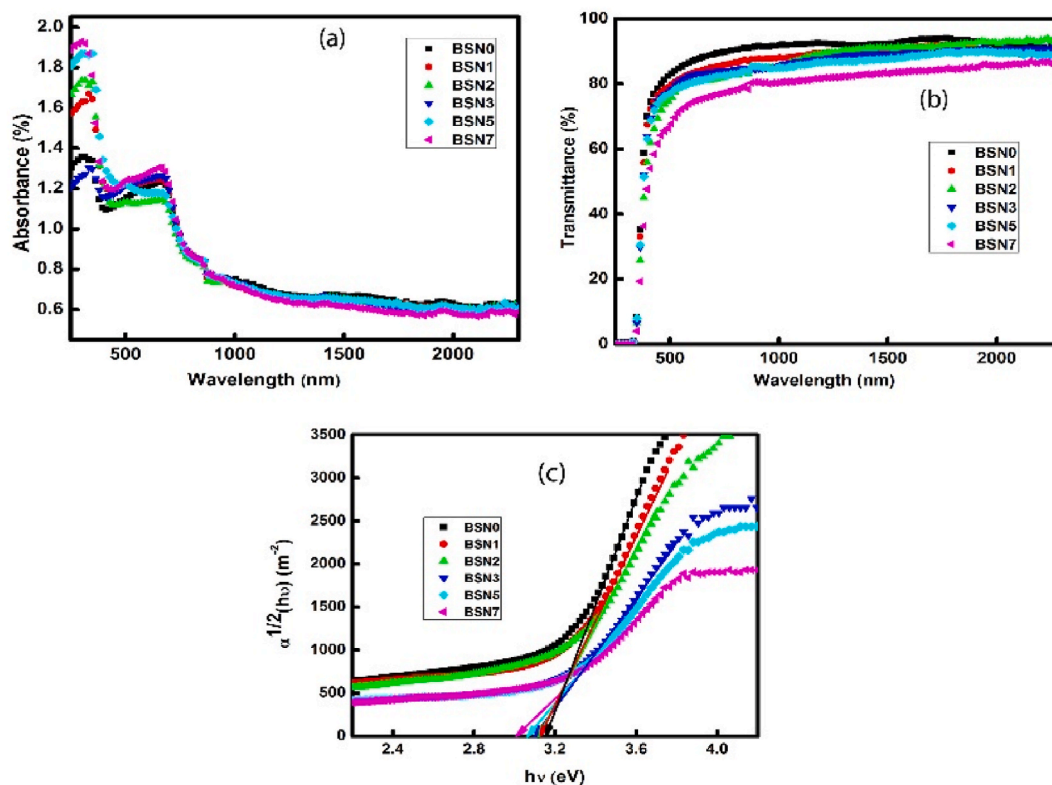| Sample Code	$\chi2$	Optical constants (at λ = 550 nm)				Average transmittance (%)	Band gap (eV)
		(n)	(κ)	(ε_r)	(ε_i)		
BSN0	2.65	2.08	0.031	4.37	0.15	90	3.15
BSN1	1.52	2.15	0.057	4.68	0.28	88	3.12
BSN2	1.53	2.14	0.057	4.68	0.29	87	3.11
BSN3	2.65	2.05	0.112	4.72	0.46	86	3.09
BSN5	2.59	2.04	0.112	4.23	0.45	85	3.06
BSN7	2.84	2.04	0.113	4.23	0.45	80	3.01

Fig. 8. a) Absorption spectra, b) transmittance spectra, and c) Tauc plot for Ni doped $BaSnO_3$ films.

in conductivity is of six orders with Ni-doping. This drastic and systematic increase of electrical conductivity on Ni doping can be due to the enhancement in carrier concentration, better crystallinity, and the highly ordered nature of the films.

4. Conclusion

Ni-doped $BaSnO_3$ films were fabricated using the PLD and analyzed their properties. XRD patterns of films reveal the poly-crystalline nature with the cubic phase of $BaSnO_3$. Further, no additional peaks in XRD patterns imply the Ni incorporation in the $BaSnO_3$ lattice. The enormous increase in intensity with Ni doping suggests the improvement of crystallinity with Ni doping. The maximum XRD intensity and the least FWHM value of the most preferred orientation (110) in BSN3 film indicate its highest crystalline quality. Morphological analysis reveals the smooth surface distribution of grains of the films. The film's thickness increases enor-mously with the Ni doping concentration, possibly due to the Induced *Magnetic* field-assisted Particle Convergence effect. The very high transmittance of the films revealed their exemplary optical quality. The Ni doping in $BaSnO_3$ resulted in bandgap renormalization. XPS analysis reveals that the Ba, Sn, and Ni ions are at +2, +4, and +3 oxidation states. The refractive index, dielectric constant, and extinction coefficient show a normal dispersion behavior in all the films. The pure and doped films exhibit visible photoluminescence. Hall-effect measurement reveals the increased carrier concentration and mobility and decreased electrical resistivity with Ni doping. The high crystallinity, high transmittance, suitable surface topography, and improved electrical performances of the Ni-doped $BaSnO_3$ films make them excellent candidates for optical devices and solar cells.

CRediT authorship contribution statement

Jibi John: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **S. Suresh:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M. Sivakumar:** Writing – review & editing. **K.G. Gopchandran:** Writing – original draft, Supervision, Project administration, Conceptualization. **V.P. Mahadevan Pillai:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.
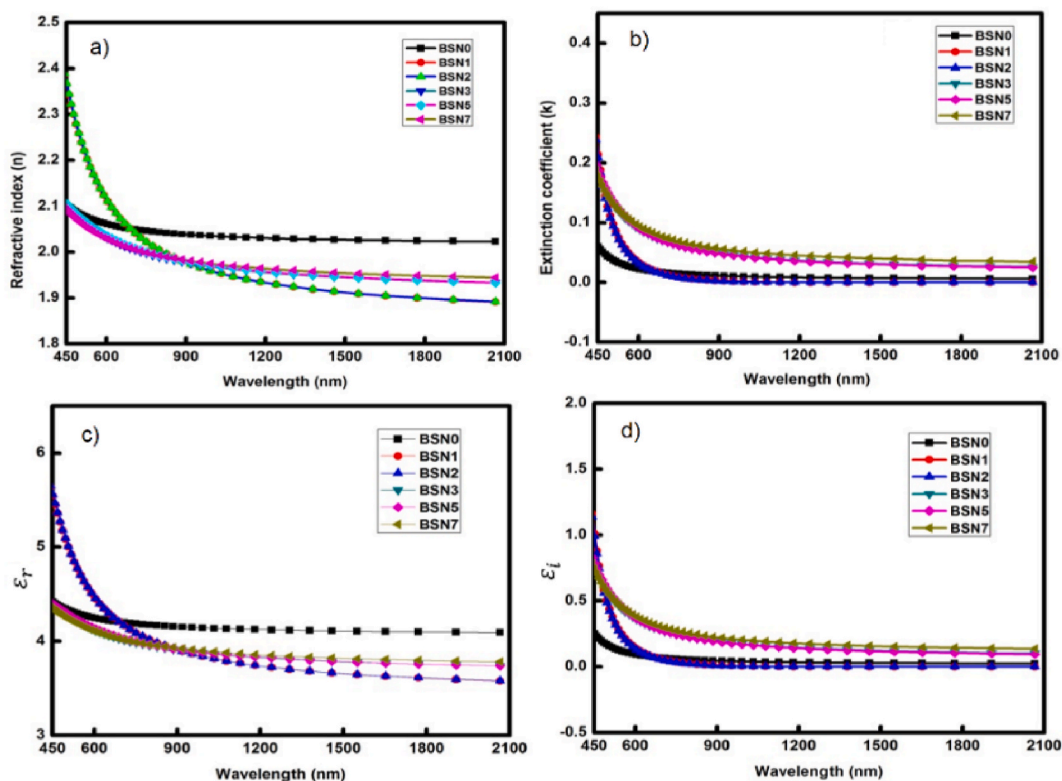
Fig. 9. Variation of optical constants with λ for Ni-doped $BaSnO_3$ films.
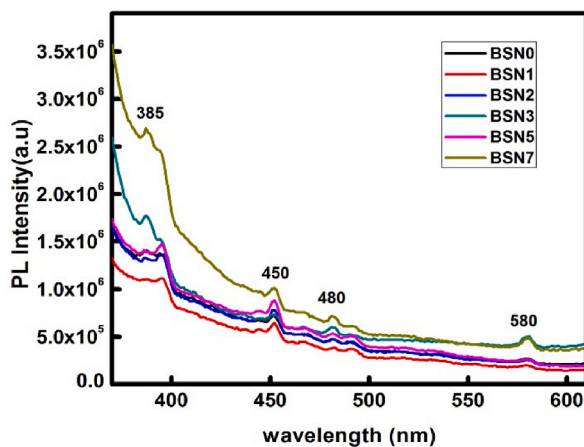
Fig. 10. PL spectra of Ni doped $BaSnO_3$ films.

Table 3
Electrical parameters of $BaSnO_3$ films.

Sample code	Carrier concentration (cm^{-3})	Electrical resistivity (Ω cm)	Mobility ($cm^2V^{-1}s^{-1}$)	Carrier type
BSN0	2.98×10^{11}	4.05×10^9	3.13	n
BSN1	1.30×10^{12}	9.99×10^5	3.51	n
BSN2	4.33×10^{12}	3.47×10^5	3.66	n
BSN3	4.37×10^{12}	3.78×10^4	9.29	n
BSN5	1.78×10^{14}	1.3×10^4	15.32	n
BSN7	3.59×10^{14}	1.13×10^3	20.93	n

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e26688.

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