Effect of substrate temperature and precursor ratio on properties of thin ZnS films sprayed by improved method

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Zinc sulphide (ZnS) thin films were prepared by improved spray pyrolysis (ISP) method. The ISP parameters, such as carrier gas flow rate, solution flow rate and substrate temperature, were controlled with an accuracy of ± 0.25 lpm, ± 1 ml/h and ± 1 °C, respectively. The solution was sprayed in a pulsed mode. The substrate temperature was optimized by analyzing substrate temperature dependent properties of thin films. The thin film deposited at a temperature of 450 °C was dense and fairly smooth with satisfactory crystallinity and very small impurity content. The effect of precursor ratio in the solution on structural, compositional and optical properties of thin ZnS films, deposited at a temperature of 450 °C, was studied. A gradual increase in band gap energy from 3.524 eV to 3.634 eV, refractive index from 2.5 to 2.9 and dielectric constant from 6.6 to 8.7 were observed with the variation of solution precursor (Zn:S) ratio from (1:2) to (1:6). The structural and compositional studies support this kind of enhancement in optical properties. The results show that the thin ZnS film prepared by ISP at the substrate temperature of 450 °C from a solution with specific precursor ratio can be used for optoelectronic and photovoltaic applications.

Keywords: *improved spray pyrolysis; pulsed mode of spray; crystalline ZnS; precursor ratio; (S/Zn) atomic ratio; optical properties*

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1. Introduction

Zinc sulphide (ZnS) is an important II – VI compound semiconductor with a large band gap of 3.65 eV [1]. It has a wide range of applications including light emitting diodes and efficient phosphors in flat panel displays [2, 3]. The ZnS material doped with metals exhibits excellent luminescent properties when excited by ultraviolet ray, X-ray, cathode ray or electrical current [1]. In the area of optics, because of its high refractive index (2.35), ZnS is used as a reflector [4] or as a part of a double layer antireflective (AR) coating, if used in conjunction with a low refractive index material, and because of its high transmittance in the visible range, it is used as a dielectric filter [5, 6]. ZnS is highly suitable as a window layer in hetero-junction photovoltaic solar cells and as

a buffer layer in CuInSe (CIS) and Cu(In,Ga)Se₂ (CIGS) based solar cells; because the wide band decreases the window absorption losses and improves the short circuit current of the cell [7, 8].

In recent past, research work in spray pyrolysis has been greatly accelerated since it is an inexpensive technique for the fabrication of large area devices in the optical and photovoltaic industry. Due to its inherent simplicity and no vacuum requirements, spray pyrolysis equipment and material costs are much lower than those of modern techniques, such as molecular beam epitaxy, H₂ plasma chemical sputtering, thermal evaporation and metal organic chemical vapor deposition. Indeed, the spray pyrolysis technique is very attractive, but consistently smooth and uniform film formation is its major problem; it is not preferably used for the thin film deposition.

In this study, attempts have been made to overcome the problems associated with conventional

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spray pyrolysis (CSP) technique and deposition of quality thin ZnS films by improved spray pyrolysis (ISP) technique. Present work aims to optimize the substrate temperature and study the influence of solution precursor (Zn:S) ratio on structural, compositional, morphological and optical properties of ISP prepared thin ZnS films.

2. Experimental

2.1. Improvement in spray pyrolysis technique

The conventional spray pyrolysis (CSP) technique has been successfully improved in order to deposit smooth crystalline and high quality thin ZnS films on an ordinary glass substrate. The improved spray pyrolysis (ISP) method had a good control over the carrier gas flow rate, solution flow rate and substrate temperature with an accuracy of ± 0.25 lpm, ± 1 ml/h and ± 1 °C, respectively. The carrier gas flow rate and solution flow rate were regulated using a rotameter and a peristaltic pump, respectively, independently of each other. In CSP the solution flow rate is influenced by carrier gas flow rate. The substrate heater temperature was controlled by proportional-integral-derivative (PID) temperature controller. During film deposition the temperature of the pyrolysis chamber wall was maintained constant by means of forced water circulation through the outer compartment of the pyrolysis chamber. A significant characteristics of the method was that the solution had been sprayed in the form of pulses at low peristaltic pump flow rate setting (< 50 ml/h). The time interval between two successive pulses was adjustable and remained almost constant as long as solution flow rate was kept fixed. A pulse mode of spray allowed the atoms to get sufficient time to migrate and occupy vacant lattice sites. Actual precursor solution flow rate was reliant on tubing factor of the peristaltic pump and its flow rate setting. For a pump flow rate setting equal to 40 ml/h, the actual solution flow rate was 75 ml/h. For a pulsed mode of spray, the peristaltic pump flow rate setting equal to 40 ml/h was found to be suitable. Film deposition time increased with the decrease in pump flow

rate setting. The formation of fine droplets and size of spray cone area is normally governed by carrier gas flow rate. In our case, it was optimized (~ 10 lpm) so as to get uniformly distributed fine droplets of precursor solution over the heater area of 4" diameter and minimize the loss of precursor solution during the spraying process. For higher carrier gas flow rates there was uneven distribution of droplets over the heater area, which could be due to the turbulence in the downward movement of droplets. Thin ZnS films were deposited at optimized ISP system parameters.

2.2. Thin film deposition and characterization

A stock solution of 0.05 M zinc chloride (G.R. grade, 98 % purity) was prepared in double distilled water. Thiourea (G.R. grade, 99 % purity) was added into 100 ml stock solution for preparing a solution of specific precursor ratio. Films were deposited on an ordinary glass substrate of a size of 2.5 cm $\times$ 1 cm $\times$ 1.2 mm. The substrate was treated with chromic acid, cleaned by ultrasonic cleaner, washed with acetone and dried under nitrogen stream before use. Dry, clean compressed air at a flow rate of 10 lpm was used to atomize the solution through the nozzle. The peristaltic pump flow rate was set to 40 ml/h, so as to spray the solution in the form of pulses. To get uniformly distributed fine droplets of the solution over a larger cone area, the distance between the nozzle and the substrate was adjusted to 35 cm. For good performance of the spray method it is known that the distance between the nozzle and the substrate should be of the order of 25 – 35 cm [9]. Both nozzle and substrate were fixed during film deposition.

In order to optimize the substrate temperature, ZnS films were deposited at substrate temperatures of 400 °C, 450 °C, 500 °C and 550 °C from a solution with precursor ratio, (1:4), since the films deposited by CSP for precursor ratio, (1:4) were of good quality [10]. Then, to study the effect of precursor (Zn:S) ratio on ZnS film structural and optical properties, it has been prepared ZnS films from solutions with precursor ratios (1:2), (1:4) and (1:6) at optimized substrate temperature. Each time

a 20 ml precursor solution was sprayed, so as to avoid the effect of viscosity on its flow rate.

Film thickness was measured using a thickness profile analyzer (KLA TENCOR P-16+). X-ray diffraction measurements of thin films were carried out using a diffractometer (BRUKER, AXS D8 ADVANCE) with CuK α radiation. The surface morphology and chemical composition of thin film was determined using SEM (JEOL, JED-2300) equipped with X-ray energy dispersive spectrometer (EDS). The optical absorption, transmission and diffuse reflectance spectra for the samples of ZnS films were obtained at room temperature in the range of 200 nm to 1200 nm using UV-VIS/NIR double beam spectrophotometer (JASCO, V-670) with a bare ordinary glass as the reference.

The crystallite size (D) of the film was calculated using Scherrer formula [11] from the full width at half maximum, FWHM (β) of diffraction curve:

$$D = \frac{k\lambda}{\beta \cos \theta} \quad (1)$$

where θ is the Bragg angle, k was taken as 0.9 and λ is 1.5406 Å, a wavelength of radiation used. The absorption coefficient (α) was obtained from an optical absorbance (A) using the formula [12]:

$$\alpha = \frac{2.303 \times A}{t} \quad (2)$$

where t is the film thickness. The direct band gap energy (E_g) of the film material was estimated from the plots based on a relationship between absorption coefficient, α and the incident photon energy, $h\nu$ [13]:

$$\alpha = \frac{B(h\nu - E_g)^{\frac{1}{2}}}{h\nu} \quad (3)$$

where B is constant.

3. Results and discussion

3.1. Pyrolysis mechanism

In ISP experiment it was used zinc chloride and thiourea as source chemicals. In the solution, ZnCl_2

decomposes as [14]:

and at elevated temperature, Zn(OH)Cl decomposes as:

The decomposition of the thiourea is given by [15]:

Finally, ZnS is formed according to the relation:

The products CH_2N_2 , H_2O and HCl , formed during pyrolysis, escaped in vapor form leaving behind the solid ZnS film on the glass substrate.

3.2. Optimization of substrate temperature

ZnS is found in nature as zinc blend (cubic, also called sphalerite) and as wurzite (hexagonal). The cubic form is stable at room temperature, while the less dense hexagonal form is stable above 1024 °C [16].

Fig. 1 shows the XRD pattern of thin ZnS films deposited at temperatures of 400 °C, 450 °C, 500 °C and 550 °C from a solution with precursor ratio, (1:4). The XRD studies revealed that the thin ZnS films deposited at temperatures of 400 °C, 450 °C and 500 °C were polycrystalline in nature, while the thin film deposited at temperature 550 °C was amorphous. The crystalline thin films exhibited preferential orientation along (111) direction of a sphalerite structure at about 28.7°. Other diffraction peaks of cubic phase, such as (220) and (311), were also detected. Preparation of crystalline thin ZnS films by CSP with cubic phase have been reported [17]. The average size of crystallites (D) for thin ZnS films, estimated by considering FWHM only of (111) diffraction curve, increased from 4.7 nm to 8.7 nm with the increase in substrate temperature from 400 °C to 500 °C. For a typical thin film deposited at a temperature of 450 °C, the estimated lattice constant (a) was 5.39 Å, which is

almost equal to the one (5.4 Å) given in the powder diffraction (JCPDS # 05-0566) data. The intensity of the (111) diffraction curve for a typical thin film is higher than that for any other films. This behavior is ascribed to good crystallinity of the thin film and greater number of crystals oriented along (111) direction. In the XRD profiles (Fig. 1), the base lines for thin films deposited at temperatures of 400 °C and 500 °C are noisy, which probably resulted from some embedded amorphous materials.

Fig. 1. XRD profiles for thin ZnS films prepared from a solution with precursor ratio, (1:4) at different substrate temperatures.

Fig. 2 shows the EDS spectra for a thin ZnS film deposited at a temperature of 450 °C from a solution with precursor ratio (1:4). The spectra show main peaks of Zn, S and Si, and peaks of O, C, Cl and Ca. The peaks of impurities O, C, and Cl may originate respectively, from the air atmosphere, and the precursors ($\text{SC}(\text{NH}_2)_2$) and (ZnCl_2). The silicon, Si and calcium, Ca peaks in the EDS spectrum come from the glass substrate, owing to thin or non continuous ZnS layer, which was formed on the substrate [18]. The chemical composition of the thin ZnS film was analyzed from the percentage by

number of atoms (at.%) of elements Zn, S, O, C and Cl present in a thin film. The at.% of elements Si and Ca was not measured. The EDS analysis showed that the typical sample contains very small amount of carbon and oxygen, and comparatively slightly higher amount of chlorine (Table 1). These values of impurities; carbon (1.2 %) and oxygen (2.29 %) are much smaller than the previously reported values [10]. The (S/Zn) and (O/Zn) atomic ratios for the thin ZnS film deposited from a solution with a precursor ratio, (1:4) at a temperature of 450 °C are about 0.90 and 0.048, respectively, which indicates that the thin film was sulphur deficient, non-stoichiometric and almost free from ZnO content. The EDS spectra for ZnS films deposited at substrate temperatures of 400 °C and 500 °C are not presented here, but their chemical composition is as given in Table 1. The (O/Zn) atomic ratio for these films, which is analogous to their ZnO content, is higher than in the film deposited at a temperature of 450 °C (Table 1).

Fig. 2. EDS spectra for thin ZnS film prepared at a substrate at temperature of 450 °C from a solution with precursor ratio, (1:4).

The thickness of all thin films was about 280 nm, which is much smaller than the reported ZnS film thickness [19]. The optical transmission spectra for thin ZnS films deposited at temperatures of 400 °C, 450 °C and 500 °C are shown in Fig. 3. Optical transmittance for thin films

Table 1. Variation of chemical composition, average crystallite size (D) and band gap energy (E_g) of as prepared thin ZnS films with substrate temperature (S.T.).

S. T. (°C)	C (at.%)	O (at.%)	Cl (at.%)	S (at.%)	Zn (at.%)	(O/Zn) ratio	(S/Zn) ratio	D (nm)	E_g (eV)
400	1.12	3.95	10.01	43.01	41.91	0.094	1.02	4.7	2.80
450	1.20	2.29	5.35	43.23	47.93	0.048	0.90	5.0	3.61
500	1.89	5.31	4.74	41.52	46.54	0.114	0.892	8.7	3.52

deposited at temperatures of 450 °C and 500 °C is close to 80 % in the visible and near infra-red region. For thin film deposited at a temperature of 400 °C the optical transmittance is low (~ 45 %), which can be due to some embedded amorphous material within the crystalline ZnS film.

The direct band gap energy (E_g) for thin ZnS films was estimated from the optical measurements. The band gap, E_g (3.61 eV) for the thin ZnS film deposited at a temperature of 450 °C, is greater than that for other thin films (Table 1). The smaller values of band gap energies for thin films deposited at 400 °C and 500 °C can be ascribed either to embedded amorphous impurities or sulphur deficiency or presence of ZnO in the film [10]. In some compounds the unit cell composition deviates considerably from the assigned chemical formula. This defect arises from the fact that some fixed lattice positions are not occupied in the unit cell resulting in the deficiency of some constituents. Such crystals are known as defect crystals and are non-stoichiometric. The deficiency of some constituents within the crystal leads to some new energy levels in the forbidden energy gap. The defect in the films caused by the deficiency of some constituents i.e. non-stoichiometry, significantly affects their electronic, dielectric, optical and other properties [13].

SEM micrographs at the same magnification ($\times = 10000$) for thin ZnS films deposited at temperatures of 400 °C, 450 °C and 500 °C from a solution with precursor ratio, (1:4) are shown in Fig. 4 (A); (B) and (C), respectively. SEM observations show that the thin ZnS film deposited at a temperature of 400 °C (Fig. 4A) is not smooth; it is in the form of patches. Its grains are not visible. Thin films deposited at temperatures of

Fig. 3. Optical transmission spectra for thin ZnS films deposited from a solution with precursor ratio, (1:4) at different substrate temperatures.

450 °C and 500 °C are slightly rough due to uneven growth of grains in different directions. Deposition of smooth and uniform film at a substrate temperature of 450 °C is possible by increasing its thickness. SEM observations also show that the grain size for thin ZnS film deposited at a temperature of 500 °C (Fig. 4C) is larger than that for thin films deposited at 450 °C (Fig. 4B). In these thin films, grains are agglomerated and grain size increases with increase in substrate temperature from 450 °C to 500 °C.

The investigation of structure, chemical composition, surface morphology and optical properties revealed that the thin ZnS film prepared from a solution with precursor ratio, (1:4) at a substrate temperature of 450 °C is crystalline and has a higher band gap and lower ZnO content. Therefore, the

Fig. 4. SEM micrographs of thin ZnS films deposited at temperatures: (A), 400 °C; (B), 450 °C and (C), 500 °C from a solution with precursor ratio, (1:4).

substrate temperature of 450 °C is the proper temperature for the deposition of thin ZnS films by ISP using aqueous solution of zinc chloride and thiourea.

3.3. Precursor ratio dependent properties

Fig. 5 shows the X-ray diffraction profiles for thin ZnS films deposited at 450 °C using solution of precursor ratios (1:2), (1:4) and (1:6). All thin films are polycrystalline and exhibit preferential orientation along the (111) direction of sphalerite phase. The observed diffractograms show good similarity with JCPDS data # 05-0566. Intensity of the ZnS (111) diffraction curve gradually increases and the curve becomes narrower with an increase in precursor ratio from (1:2) to (1:6), indicating a gradual improvement in the film crystallinity. The FWHM of (111) diffraction curve was considered for estimation of average size of crystallites (D). The FWHM that corresponds to (111) diffraction curve decreases and the average crystallite size (D) increases from 4.0 nm to 5.6 nm with the increasing thin film order from (1:2) to (1:6) (Table 2). This behavior is ascribed to a gradual reduction in lattice defects and imperfections with the increase in solution precursor ratio [10].

The EDS analysis of thin ZnS films revealed that the (S/Zn) atomic ratio increases from 0.83 to 1.01 with an increase in solution precursor ratio from (1:2) to (1:6) (Table 2), which indicates an improvement in film stoichiometry, and thereby reduction in lattice defects and imperfections. As the impurity (C, O and Cl) levels in the ZnS film deposited at a temperature of 450 °C are very low,

Fig. 5. XRD profile for thin ZnS films prepared at a substrate temperature of 450 °C using solution of different precursor ratios.

the sulphur deficiency in the film is the only primary source of lattice defects. An increase in average crystallite size (D) with the increasing (S/Zn) atomic ratio indicates a reduction in lattice defects and improvement in crystallinity of the ZnS films. The value of (S/Zn) atomic ratio equal to 1.01 signifies that the thin ZnS film, obtained for the (1:6) precursor ratio, was almost stoichiometric with very small zinc deficiency. The thin films for (1:2) and (1:4) precursor ratios are sulphur deficient and non-stoichiometric. Non-stoichiometry

Table 2. Variation of chemical composition, average crystallite size (D), band gap energy (E_g), refractive index (n) and dielectric constant (ϵ) of as prepared thin ZnS films with solution precursor ratio.

Precursor (Zn:S) ratio	O (at.%)	S (at.%)	Zn (at.%)	(O/Zn) ratio	(S/Zn) ratio	D (nm)	E_g (eV)	n*	ϵ^*
(1:2)	2.71	40.90	49.33	0.055	0.83	4.0	3.524	2.5	6.6
(1:4)	2.29	43.23	47.93	0.048	0.90	4.9	3.608	2.6	7.8
(1:6)	2.29	45.33	44.75	0.051	1.01	5.6	3.634	2.9	8.7

*Estimated at 546 nm wavelength.

of compounds leads to structural defects, which have an adverse effect on their optical properties [20]. For as prepared ZnS films from (1:2) to (1:6), the (O/Zn) atomic ratio is around 0.05; it means that in these films the content of ZnO was too small.

The texture coefficient $TC(hkl)$ represents the texture of the particular plane concerning the preferential crystal orientation, defined as [21]:

$$TC(hkl) = \frac{I(hkl)/I_o(hkl)}{(1/n) \sum_n [I(hkl)/I_o(hkl)]} \quad (4)$$

where $I(hkl)$ is the XRD intensity, $I_o(hkl)$ is the standard intensity of the plane (hkl) taken from the JCPDS data, and n is the number of diffraction peaks considered.

The values of $TC(hkl)$ higher than 1 indicate the abundance of crystallites in the direction perpendicular to the (hkl) plane. The variations of $TC(hkl)$ in planes (111), (220) and (311) for the films with precursor ratio are presented in Fig. 6. It is seen that the texture coefficient (TC) in (111) plane for all thin films is the highest. The $TC(111)$ increases with the increasing film order from (1:2) to (1:6) and becomes maximum (~ 1.64) for thin film, (1:6), while $TCs(hkl)$ in planes (220) and (311) gradually decrease; the films tend to orient from polycrystalline to single crystalline with the increasing (S/Zn) atomic ratio from 0.83 to 1.01. Thus, it can be concluded that the texture coefficient in a certain (hkl) plane ((111) for the ZnS film) depends upon (S/Zn) atomic ratio i.e. the extent, to which the film is stoichiometric.

Fig. 7 and 8 show optical transmission spectra and absorption spectra, respectively, for thin ZnS

Fig. 6. Variation of $TC(hkl)$ for thin ZnS films in planes (111), (220) and (311) with solution precursor ratio.

films deposited at a temperature of 450 °C using solution of precursor ratios (1:2), (1:4) and (1:6). The optical transmittance of all thin films is close to 80 % in the visible and near infra-red region and 70 % in the short wavelength region (350 nm to 550 nm). The optical absorption edges (Fig. 8) for thin films are nearly straight, which indicates that the thin films deposited by ISP were almost homogeneous in the shape and size of grains, and in the distribution of constituents. The thickness of all thin films was about 280 nm. The optical properties of thin films were determined from optical absorbance and diffuse reflectance measurements.

The direct band gap (E_g) for thin ZnS films was calculated by extrapolating the linear portion of the square of $(\alpha h\nu)$ against incident photon energy

Fig. 7. Optical transmission spectra for thin ZnS films deposited at a substrate temperature of 450 °C using solutions of different precursor ratios.

Fig. 8. Optical absorption spectra for thin ZnS films deposited at a substrate temperature of 450 °C using solution of different precursor ratios.

($h\nu$) plots up to the intersection with x-axis (Fig. 9). The E_g increases from 3.524 eV to 3.634 eV with an increase in (S/Zn) atomic ratio from 0.83 to 1.01 (Table 2). This type of functional relationship between band gap (E_g) and (S/Zn) atomic ratio for thin ZnS film, prepared from a solution with same precursor ratios i.e. (1:2), (1:4) and (1:6) has been not observed in previous work [19].

Metal excess or deficient compounds are defective compounds [22]. Metal excess defects are

Fig. 9. Square of ($\alpha h\nu$) plotted against incident photon energy, $h\nu$. The straight lines correspond to extrapolated linear portion of plots.

caused by interstitial cations. This type of lattice defect is rather like Frankel defect. It has an adverse effect and as a result the band gap energy of a compound decreases [13]. Thin ZnS films (1:2) and (1:4) were metal (zinc) excess or sulphur deficient compounds. The E_g for thin film, (1:2) is the lowest (3.524 eV), which is ascribed to greater number of lattice defects due to comparatively higher sulphur deficiency. An increase in E_g for thin ZnS films of increasing order from (1:2) to (1:6) can be attributed to the decrease in lattice defects and impurities within thin films with an increase in their (S/Zn) atomic ratio (Table 2). The band gap, E_g ($\sim$ 3.634 eV) for thin ZnS film, (1:6) is close to the typical value for bulk ZnS ($\sim$ 3.65 eV). This is because of its good crystallinity, bigger crystallite size and lower ZnO content [10].

Refractive index (n) for thin ZnS film was determined using the formula [13]:

$$R = \frac{(n-1)^2}{(n+1)^2} \quad (5)$$

where R is the reflectance. Diffuse reflectance of thin ZnS films was used for estimating their refractive indices. Average diffuse reflectance of all thin films (1:2), (1:4) and (1:6) in the visible and near infra red regions was about 16 %. The values of n

(estimated at 546 nm) for all ISP prepared thin ZnS films (Table 2) are little higher than the previously reported value (~ 2.35) [23]. Refractive index n for as prepared thin ZnS films increases from 2.5 to 2.9 with the increase in (S/Zn) atomic ratio from 0.83 to 1.01.

The normal dielectric constant (ϵ) for thin ZnS film was estimated by [13]:

$$\epsilon = n^2 - k^2 \quad (6)$$

where k is the extinction coefficient and is given by [13]:

$$k = \frac{\alpha \times \lambda}{4\pi} \quad (7)$$

The normal dielectric constant ϵ for thin ZnS films (estimated at 546 nm) increases from 6.6 to 8.7 with an increase in (S/Zn) atomic ratio from 0.83 to 1.01 (Table 2). The values of ϵ for all as prepared thin ZnS films are higher than that for chemical bath deposited thin ZnS film (~ 6.0) [23]. Dielectric constant, ϵ for film, (1:6) is larger than that for other films (1:2) and (1:4). This behavior can be ascribed to less lattice defects, good crystallinity and almost perfect stoichiometry of thin film, (1:6).

4. Conclusion

Polycrystalline thin ZnS films of sphalerite structure with preferential orientation along (111) direction were prepared successfully by improved spray pyrolysis (ISP) technique. It has been applied an ISP system operating in a pulsed mode for deposition of these films and obtained good results. The study revealed that the substrate temperature of 450 °C is the proper temperature for preparation of thin ZnS films by ISP using aqueous solution of zinc chloride and thiourea. The thin film deposited at the temperature of 450 °C from a solution with precursor ratio, (1:4) was fairly smooth. It was possible to deposit smooth ZnS films by increasing their thickness. The obtained good quality thin ZnS films deposited at the temperature of 450 °C using solution of precursor ratios (1:2), (1:4) and (1:6) included ZnS with very small carbon and oxygen contents; ZnO content in the thin films was very

small. An increase in (S/Zn) atomic ratio for thin ZnS films from (1:2) to (1:6) showed an enhancement in film crystallinity and stoichiometry, which was accompanied by an increase in film crystallite size, direct band gap energy, refractive index and dielectric constant.

Thin ZnS films prepared by ISP from a solution with precursor ratio, (1:6) were found to have good stoichiometry, very small ZnO content, optical transmission of about 80 % in the visible and near infra-red regions and about 70 % in the short wavelength region, direct band gap of 3.634 eV, refractive index of 2.9, and normal dielectric constant of 8.7. These features of ISP prepared thin ZnS films make the films more appropriate for optical and photovoltaic applications such as dielectric filters, electroluminescent materials, reflectors, antireflective coatings and buffer layers in Cu(In,Ga)Se₂ absorber based solar cells.

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