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Comparative studies on the structural, morphological, optical, and electrical properties of nanocrystalline PbS thin films grown by chemical bath deposition using two different bath compositions

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Abstract

High-quality lead sulfide (PbS) thin films were synthesized by chemical bath deposition from two baths with different compositions. One of them (bath-I) contained an aqueous solution of lead acetate, thiourea, sodium hydroxide, and the second (bath-II) had additional triethanolamine. The introduction of triethanolamine reduced the grain size and increased the optical band gap of the PbS nanoparticles. The structure, morphology, and optical properties of the obtained films were investigated and compared with respect to the deposition time. X-ray diffraction data were used to obtain the crystallite size, lattice constant, and strain of the films. Atomic force microscopy results show that the roughness and rms-surface slope of the samples obtained from bath-I (PbS-I) were higher than those of bath-II (PbS-II) samples. PbS thin films with high reflectance (~61%) in the near-infrared region, which is important in our solar system, were obtained. The band gap, extinction coefficient, and refractive index of the samples were calculated. Furthermore, Raman analysis was performed and electrical properties of the samples were studied.

1. Introduction

The preparation of nanostructure semiconducting materials has attracted more attention from a fundamental point of view because of its increasing number of potential technological applications. The preparation of chalcogenide semiconductors can be found in some recent reports. In particular, compounds of IV–VI semiconductor nanostructure thin films as optoelectronic materials have been the focus of interest. PbS is an important intrinsic semiconductor material in micro- and nanostructured thin films because of its various technological applications in IR detectors, solar absorbers, optical switches, heavy-metal concentration monitoring, electrochemical sensors for hydrogen sulfide (H₂S), and semiconductor active layers in common-gated thin-film transistors.

Many research attempts have been devoted to the controlled synthesis of PbS nanoparticle thin films of varying size. Both physical and chemical methods of deposition have been used. Vacuum evaporation, hot-wall epitaxy, molecular-beam epitaxy, and pulsed laser deposition are among the most successful physical methods for PbS synthesis. The most commonly used chemical methods include spray pyrolysis, chemical bath deposition (CBD), successive ionic layer adsorption and reaction (SILAR)
[16], electrochemical deposition [17], and hydrothermal method [18]. The chemical deposition methods are low-cost processes and the films are of comparable quality to those obtained by more complicated and expensive physical deposition processes. Among these chemical methods, CBD is of special interest as it is a simple and highly efficient method. It is also known as solution growth, controlled precipitation, or simply chemical deposition. It allows potent and adjustable control of the size and surface density of nanoparticles. Therefore, it can be used for preparation of high-quality nanocrystalline PbS films with control of the deposition parameters such as stirring period, reaction time, bath temperature, solution pH, and added impurities. The range of materials that can be deposited by CBD and microwave-assisted CBD is wide [13–15, 19].

Comparison of the properties of PbS thin films obtained from different chemical baths have been performed by some researchers [20–23]. Kaci et al. investigated the influence of polyethylene glycol-300 (PEG 300) on the properties of nanostructured lead sulfide thin films. Their results indicate that the particle size of PbS thin films is reduced upon addition of PEG 300 [24]. Preetha et al. prepared PbS thin films by the SILAR method and used triethanolamine (TEA) as the complexing agent [16]. They also reported a comparative study of characteristic properties of as-prepared PbS thin films by the CBD method after thermal treatment through two different routes [25]. A comparative study has been performed on properties of PbS thin films grown by SILAR by using acidic, neutral, and alkaline cationic reaction baths with TEA [26].

In the present study, TEA was used as the complexing agent in one of the baths (bath-II), and PbS films were prepared without TEA (bath-I) by the CBD method to prepare nanocrystalline PbS films. By choosing equal molarities of solutions in bath-II, high reflectance (about 61%) in the near-infrared (NIR) region was obtained. We present a full comparative study of size-dependent properties of PbS thin films obtained from two different chemical bath solutions. The morphology of the prepared films was investigated by transmission electron microscopy (TEM), scanning electron microscopy (SEM), and atomic force microscopy (AFM). The optical and structural parameters, especially the variations of strain, lattice constant, and growth orientation with grain size of the films, were calculated and compared.

2. Experimental details

Two baths with different chemical composition were used for the preparation of PbS films. All chemicals were of analytical grade (Merck) and were used as received without further purification. The first bath (bath-I) contained an aqueous solution of 0.175 M lead acetate, 0.085 M thiourea, and 0.3 M sodium hydroxide. The second bath (bath-II) contained an aqueous solution of 0.3 M lead acetate, 0.3 M thiourea, 0.3 M TEA, and 0.6 M sodium hydroxide, which are the optimal molar concentrations for the deposition of PbS films. Both solutions were prepared in deionized water. The temperature and pH value of the bath were 25 °C (room temperature) and 11, respectively. Overall, the prepared films were homogeneous, smooth, and adherent to the substrate.

In the CBD method, the deposition of PbS occurs only when the ionic product \([\text{Pb}^{2+} \times [\text{S}^{2-}]]\) exceeds the solubility product of PbS \(K_{\text{sp}} \approx 10^{-28}\) at 25 °C [14]; therefore, the concentration of lead and sulfur ions have to be controlled very carefully during growth. Film growth takes place by ion-by-ion or by cluster mechanism. In alkaline solution, thiourea decomposes and produces HS\(^-\). In fact, most of the sulfur ion is in the form of HS\(^-\) rather than \(S^{2-}\). HS\(^-\) interacts with hydroxide (OH\(^-\)) and releases \(S^{2-}\) ions, which precipitate Pb\(^{2+}\) ions from the solution. In bath-I, the fundamental reaction takes place between lead acetate and thiourea in the presence of NaOH. The possible reaction for PbS thin film formation is as follows [14]:

\[
\text{SC(NH}_2\text{)}_2 + \text{OH}^- \rightarrow \text{CH}_3\text{N}_2\text{H}_2 + \text{H}_2\text{O} + \text{HS}^- \tag{1}
\]

\[
\text{HS}^- + \text{OH}^- \rightarrow \text{H}_2\text{O} + \text{S}^{2-} \tag{2}
\]

\[
\text{Pb}^{2+} + \text{S}^{2-} \rightarrow \text{PbS} \tag{3}
\]

With the addition of TEA as complexing agent in bath-II, the metal complex is formed [14]:

\[
\text{Pb}^{2+} + \text{TEA} \rightarrow \{\text{Pb(TEA)}\}^{2+} \tag{4}
\]

Complexing agents help to control the reaction rate. Formation of this metal complex reduces the concentration of free Pb\(^{2+}\) ions below the level required for precipitation of solid-phase Pb(OH)\(_2\) [26]. The formation of nucleation centers through Pb(OH)\(_2\) in the reaction bath is the first step for growth of PbS film on glass substrates. With the formation of Pb(OH)\(_2\), the color of the reaction bath became white and turbid. The mixture gently changed to cloudy dark brown as PbS was precipitated from the solution. It can be deduced from this reaction that film formation can take place not only by simple ion-by-ion or cluster mechanism, but also by metal–complex mechanisms [13, 14]. In the metal–complex decomposition mechanism, the ions diffuse to the substrate to form suitable nuclei and to grow or exist as complexed colloids of nuclei in the solution. Finally, this initial nucleation is exposed to chemical interactions in the bath to form a thin film. The growth of PbS films can be explained by the hydroxide cluster and complex decomposition mechanisms. As a result, the deposition rate is slower and thinner layers are formed in this case.

The thicknesses of the films were measured by using Rutherford backscattering spectroscopy (RBS). This analysis was carried out at a scattering angle of 165° by using a 2 MeV He\(^{2+}\) ion beam. The structure of the films was analyzed by X-ray diffraction using a D8-Advance Bruker with Cu K\(\alpha\) radiation (\(\lambda = 1.5406\) Å). Optical studies were performed on a Fourier transform infrared spectrophotometer (ATI Mattson Genesis Series) and a UV–vis double beam spectrophotometer (Lambda-45 Perkin-Elmer). The surface morphology of the deposited films was characterized using SEM (XL 30-Philips) and AFM-mode scanning probe microscopy (SPM; Dual Scope C-21 DME). Microscopy was performed on a Phillips EM 208S transmission electron microscope at an accelerating voltage of 100 kV. Raman analysis was carried out on an Almega Thermo Nicolet
dispersive Raman spectrometer with 30 mW laser power and 532 nm wavelength.

3. Results and discussion

3.1. RBS study

RBS spectra of two typical thin films obtained from bath-I and bath-II are shown in Fig. 1. The contribution of Si (substrate) in the presence of Pb, S, and O was identified. Ca also was observed in the PbS-II films. From the RBS data, the thicknesses of the PbS-I and PbS-II films were estimated to be 300–1000 nm and 40–120 nm, respectively.

3.2. Structural study

Fig. 2 shows the X-ray diffraction patterns of PbS films obtained from bath-I (Fig. 2a) and bath-II (Fig. 2b). The patterns in Fig. 2a clearly have diffraction peaks at 26.41°, 30.50°, 43.50°, 51.47°, 53.86°, 71.36°, and 79.36° which, respectively, correspond to the (111), (200), (220), (311), (222), (331), (420), and (422) Miller planes of the PbS phase with cubic structure (galena). However, PbS-II films produced only peaks at 26.22°, 30.36°, 43.48°, and 51.24° corresponding to the Miller planes (111), (200), (220), and (311), respectively (Fig. 2b). The intensity of the peaks in PbS-I films is higher than those of the PbS-II films because the thickness of the PbS-I films was larger than that of the PbS-II films. The preferred growth orientation in the PbS-I films changed from (200) to (111) with increasing deposition time. However, the preferred orientation in the PbS-II films in the (200) plane was observed with increasing deposition times. It was verified that the relative intensity of the X-ray diffraction (XRD) peaks changes with the immersion time of the substrate in solution, and with its composition in the CBD method. Seghaier et al. [27] reported that for t = 70 min, the intensity of (200) peaks for their PbS thin films decreased. For our samples obtained from bath-I, the intensity of (200) decreased after t = 3 h. For the samples obtained from bath-II, (200) is the dominant peak (in the presence of TEA). Kannianen et al. showed that the highly oriented (200) can be grown when TEA complexation was used [28]. The diffraction peaks observed in Fig. 2 correspond to standard JCPDS files (no. 5592).
The average crystal size \(D\) was calculated by using Debye–Scherer’s formula:

\[
D = 0.9 \lambda / \beta \cos \theta,
\]

where \(\lambda\) is the wavelength (1.5406 Å), \(\beta\) is the full width at half maximum of the peak (in radians), and \(\theta\) is the diffraction angle of the XRD peak. The role of crystallite size on the electrical and optical behavior of the films is very important. The crystallite size obtained for samples prepared from bath-I and bath-II were 180–200 nm and 8–21 nm, respectively (Table 1). The crystallite sizes obtained from bath-I were greater than those from bath-II. When TEA was added to the chemical bath, fewer ions were available for film formation, so thinner films formed, resulting in the formation of small grain sizes.

The lattice constant, \(a\), of the films was calculated using the following equation:

\[
\frac{1}{a^2} = \frac{h^2 + k^2 + l^2}{\lambda^2}.
\]

The mean values of the lattice constant for the PbS-I and PbS-II samples were 5.9207 and 5.9173 Å, respectively (Table 1). The reference data of the bulk PbS crystals is 5.9360 Å. As a reported value for the PbS thin films (5.9195 Å) [29]. The lattice constant of the PbS films, presented in Table 1, were calculated and their potential applications is important. Strain values of the PbS films, presented in Table 1, were calculated using the following equation:

\[
\varepsilon = \frac{\beta \cos \theta}{4},
\]

where \(\theta\) and \(\beta\) are the same as in Eq. (5). Strain values of the PbS-I films are smaller than those of the PbS-II samples. It can be seen that the strain value decreased with increasing deposition time, and it was related to the crystallite size [36]. The strain data for PbS-I and PbS-II films, are low and compatible with the data reported in the literatures, respectively [30,31].

### 3.3. SEM and TEM studies

The surface morphology of the films was studied by SEM. Fig. 3a and b shows the SEM images of the PbS-I and PbS-II thin films, respectively, at two different deposition times. It can be seen from the SEM images that both groups displayed a continuous and compact polycrystalline film with well-defined grain boundaries. The grain sizes were estimated to be 180–230 nm and 9–35 nm for PbS-I and PbS-II films, respectively. The crystallite sizes in the SEM images are greater than that suggested by the XRD patterns. Pentia et al. also made the same comparison for their samples obtained from different baths [20]. For the thicker film, they used Bi ions (Bi(NO₃)₃) in the bath and obtained PbS films with an average grain size of 250–300 nm. However, upon deposition of thinner films performed without Bi ions, the grain size of obtained films was about 50 nm. As clearly seen (Fig. 3a and b), large isolated clusters formed on the surface of the PbS films. Two different phenomena explain the formation of these aggregates. First, the formation of aggregates in the chemical solution is related to nucleation around impurity molecules on the substrate surface [32]. Second, there are two growth mechanisms for CBD, namely, ion-by-ion and cluster-by-cluster mechanisms. In CBD, these two mechanisms occur randomly and the aggregates form in the cluster-by-cluster mechanisms [33]. High-resolution TEM images of the precipitated, powdered PbS-I sample deposited at \(t = 4\) h are also displayed (Fig. 3a). Most of the crystals were cubic, having an average length of 230 nm.

Fig. 4 presents TEM images of the PbS-I and PbS-II samples deposited at \(t = 4\) h. The morphology of the PbS-I sample was a cube-shaped crystal with an average size of about 235 nm (Fig. 4a). Addition of TEA to bath-II hindered the growth of PbS nanocrystals due to formation of the metal complex, resulting in smaller PbS crystals. The average crystal size of PbS-II film was about 37 nm, consistent with the SEM results.

### 3.4. AFM studies

Fig. 5 shows the surface images of PbS thin films at two different deposition times, obtained by AFM. The surfaces of the prepared films were very smooth. The roughness values (rms) changed from 78.3 to 174 nm and from 8.5 to 50.2 nm for PbS-I and PbS-II films, respectively (Table 2). Das et al. reported that the rms roughness of their nanocrystalline PbS films was in the range of 11.8–43.7 nm [31]. Following this trend, we can conclude that the surface roughness increases with the deposition time. In addition, the roughness values of the PbS-I films are greater than the PbS-II films. The rms surface slope is given as following equation:

\[
S_{\text{rms}} = \sqrt{\frac{1}{A} \int \int_{0}^{L_x} \left( \frac{\partial z(x,y)}{\partial x} \right)^2 + \left( \frac{\partial z(x,y)}{\partial y} \right)^2 \, dx \, dy}
\]
Fig. 3. SEM image of (a) PbS-I (inset in $t = 4$ h: high-resolution SEM image of precipitated powdered sample) and (b) PbS-II thin films at two different deposition times.

Fig. 4. TEM image of (a) PbS-I and (b) PbS-II thin films deposited at $t = 4$ h.
where $A$ is the area under analysis corresponding to $2 \mu m \times 2 \mu m$ scans in our experiment. (This formula is taken from the SPM system data.) Estimated values of $S_{dq}$ for the PbS-I and PbS-II films are summarized in Table 2. The corresponding $S_{dq}$ values of the PbS-I samples are greater than those of the PbS-II films; this indicates a greater surface reflectance coefficient of samples obtained from bath-II (smaller values of $S_{dq}$ corresponds to higher reflectivity).

Furthermore, the corresponding $S_{dq}$ parameter of all prepared samples from the two baths increased with deposition time.

### 3.5. Optical properties

Fig. 6 illustrates the transmittance of PbS thin films prepared from the two baths in the spectral range of

![AFM images of (a) PbS-I and (b) PbS-II thin films at different deposition times.](image)

<table>
<thead>
<tr>
<th>Bath-I</th>
<th>Bath-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposition time (h)</td>
<td>1</td>
</tr>
<tr>
<td>rms (nm)</td>
<td>78.3</td>
</tr>
<tr>
<td>$S_{dq}$</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Table 2
Values of rms and $S_{dq}$ of PbS thin films obtained from two different baths at different deposition times.
300–2600 nm. It shows that for films from bath-I prepared at deposition times of 1, 2, 3, and 4 h, the transmittance began to increase at 700, 800, 900, and 1000 nm, respectively, up to a maximum value of radiation wavelength of 1840–2400 nm. The maximum transmission value is equal to 84.5% for the PbS film that was deposited for 1 h (Fig. 6a). For layers obtained from bath-II, the transmittance began to increase at 300–700 nm at different deposition times. The maximum value of transmittance in this case was 89% for layers deposited in 1 h at 2500 nm wavelength (Fig. 6b). The films of both baths showed a decrease in transmission with increasing thickness of the films.

Figs. 6 and 7 show the transmissions and reflectance spectra of the samples. The range 1000–2600 nm in the reflectance spectrum has a clear interference pattern with several maxima and minima. The layers deposited at \( t = 1 \) and 2 h have maximum reflectance values of 52% at 1277 nm and 57% at 2058 nm, which are greater than those of the other two layers (Fig. 7a). The reflectance increased slightly up to 61% (\( \lambda = 810 \) nm) and 57.5% (\( \lambda = 1200 \) nm) for layers from bath-II at deposition times equal to \( t = 1 \) and 2 h, respectively (Fig. 7b). The reflectance values obtained for PbS-II layers deposited in \( t = 1 \) and 2 h are higher than the reported values in the literature [27,33–35]. This result shows that the molarity of our solutions was suitable. The high reflectance value in the NIR region and low transmittance value in the visible region suggests that these films can be applied in solar control systems. The reflectance of this kind of PbS films is comparable to those of metallic films such as Ni, Au, and Al [34,36]. In the spectral range 300–1200 nm, the reflectance values decreased with increasing deposition time. This phenomenon can be explained by the film morphology. As the film thickness increases, the grain size and the surface roughness increase as well, leading to a decrease in reflectance [34]. However, in the spectral range 1200–2600 nm, there was no correlation in the variation of the reflectance values with the deposition time.

The band gap of the samples was estimated by using the Tauc relation [37,38]:

\[
(\alpha h\nu)^2 = K(h\nu - E_g)
\]

where \( K \) is a constant and \( E_g \) is the band gap energy. Values of the optical absorption coefficient (\( \alpha \)) were calculated from the following equation:

\[
\alpha = - \ln T/d
\]

where \( d \) is the film thickness and \( T \) is the transmission.

Fig. 8 presents the functional dependence of \((\alpha h\nu)^2\) versus \((h\nu)\). This variation is a straight line, which confirms...
the direct optical transition. As shown in Fig. 8a and b, the optical band gap of the PbS thin films obtained from bath-I and bath-II increased from 1.39 to 1.55 eV and from 2.38 to 2.75 eV when the deposition time decreased from 4 to 1 h. For the PbS bulk, the value of the band gap at room temperature was 0.41 eV. The higher values of the band gap can be explained by the quantum confinement effects [5,13]. The absorption coefficient is also related to the extinction coefficient \( \kappa \) in the following equation:

\[
\kappa = \frac{\alpha \lambda}{4\pi}.
\]

The calculated extinction coefficients of PbS thin films in the visible and near-infrared region are in the order of 0.24–0.08, and are comparable to the reported values for PbS films [39,40], indicating good surface homogeneity. The refractive index (\( n \)) may be calculated from the relation as follows [41]:

\[
n = \frac{1 + R}{1 - R} + \left[ \frac{4R}{(1 - R)^2 - \kappa^2} \right]^{1/2}.
\]

If the mean value of \( R \) is 0.35–0.45 and \( \kappa \) values are 0.1–0.2 in the wavelength range 1000–2500 nm, then the calculated \( n \) values of PbS thin films from the two groups of samples should be about 3.88–4. It can be seen that the \( n \) value of PbS thin films are comparable to those of the PbS bulk crystal (3.9–4.1) [42,43]. As the refractive index in these materials changes with the wavelength of light, it is possible to use these materials in optoelectronic devices.

### 3.6. Raman study

It has been demonstrated that Raman spectroscopy is a fast and nondestructive tool for determining the properties of crystalline materials. In particular, it can be a useful tool for investigating multi-exciton materials as a probe of the exciton–phonon coupling through the Frohlich interaction. There can be some ambiguities in the interpretation of the Raman spectra of PbS because PbS has a NaCl crystal structure belonging to the \( Fm3m \) space group, in which first-order Raman scattering is forbidden [44].

Raman spectra for the two samples PbS-I and PbS-II collected by using a laser power of 30 mW with 532 nm excitation line at room temperature are displayed in Fig. 9. The spectrum of PbS-I contains bands at 140, 338, 425, 502, 590, 709, 790, and 933 cm\(^{-1}\) for the PbS-II film. The major bands are at 141, 287, 500, 750, and 938 cm\(^{-1}\). The strong band centered at 140 cm\(^{-1}\) originates from the combination of longitudinal and transverse acoustic phonon modes in PbS crystals [45]. This band is similar to the 150 cm\(^{-1}\) peak [46] recorded at 4.3 K by excitation at 584 nm and to the 155 cm\(^{-1}\) peak [47] recorded by excitation at 632.8 nm. The strong band centered at 140 cm\(^{-1}\) originates from the combination of longitudinal and transverse acoustic phonon modes in PbS crystals [45]. This band is similar to the 150 cm\(^{-1}\) peak [46] recorded at 4.3 K by excitation at 584 nm and to the 155 cm\(^{-1}\) peak [47] recorded by excitation at 632.8 nm. According to earlier reports [48,49], the peak around 338 cm\(^{-1}\) is due to vibrational bands of tetragonal PbO. The peaks at around 425 and 590 cm\(^{-1}\) of the PbS-I films come from the first and second overtones of fundamental longitudinal optical (LO) phonon modes 2 LO and 3 LO [46,50], respectively. The peak around 287 cm\(^{-1}\) of the PbS-II film is related to PbO formation due to photodegradation of PbS [51]. The bands at around 500 cm\(^{-1}\) of the PbS-I and PbS-II films might be due to formation of PbO as a result of laser photooxidation products of PbS [52]. Similarly, Ovsyannikov et al. observed a peak at around 510 cm\(^{-1}\) and ascribed it to the formation of PbO\(_2\) [53]. Peaks in the range 600–1000 cm\(^{-1}\)
relate to XSO₄ species arising from anion oxidation in the PbS nanocrystals, where X can be attributed to Pb, PbO-Pb, 3PbO-Pb, or 4PbO-Pb [48]. The peaks at 933 and 938 cm⁻¹ in the spectra of PbS-I and PbS-II films, respectively, may be due to PbSO₄. They are similar to peaks at 957–969 cm⁻¹ reported for PbS QDs and thin films that were prepared and analyzed under different conditions [47,48,51,54].

The XRD pattern of our PbS thin films confirms that they consisted of pure cubic PbS without sulfates. Thus, the sulfates and oxysulfates in the samples originated from the laser photooxidation products of PbS, which are consistent with results reported previously [48]. In addition, no peak corresponds to the surface phonon mode (205 cm⁻¹ [55]) in the Raman spectrum of our samples, indicating that there were few defects on the surface of the PbS structure [56]. It has been demonstrated that the difference in phonon frequency positions and intensities is highly related to differences in particle size, excitation wavelength, temperature, and confinement of optical phonons [45–47,55]. It has also been shown that with decreasing crystalline size, the peak intensity increases because of the increase in surface-to-volume ratio [44,55]. Thus, in the case of our samples, the crystal size of the PbS-II film was smaller than that of PbS-I film, and the peak intensity of the Raman spectrum of PbS-II is higher than that of the spectrum of the PbS-I film.

### 3.7. Electrical study

The electrical resistance per square, $R_\square$, is probably the most important electrical property that characterizes thin films. It depends on the thickness, material type, and structure. $R_\square$ of the PbS thin films prepared at different deposition times were determined by the two-probe method using silver electrodes. The measured dark resistance ($R_{\square\text{D}}$), photosensitivity ($S = (R_{\square\text{D}} - R_{\square\text{C}})/R_{\square\text{C}}$), and thickness of the PbS films are summarized in Table 3. The data show a strongly increased sheet resistance of the PbS-II film compared with the PbS-I film, which is due to the small crystallite sizes. This suggests a drastic reduction of the carrier concentration or the mobility in these samples [57]. The normal sheet resistance allows for good photoconductive properties of PbS-I layers, which have potential applications in photoconductor detectors. Because of the high sheet resistance of the PbS-II films, they cannot be applied in photoconductor detectors. However, they can be applied in solar control systems [20,34] because of their special optical properties, as discussed in previous sections.

### 4. Conclusions

We successfully deposited PbS thin films from two different baths using the CBD method. The polycrystalline structure of the films was studied by XRD. The average crystallite sizes of PbS-I and PbS-II films obtained from XRD data were 180–200 nm and 6–21 nm, respectively. The strain in the PbS-I and PbS-II thin films was found to be within the range $1.22 \times 10^{-3}$ to $0.65 \times 10^{-3}$ and $4.9 \times 10^{-3}$ to $2.1 \times 10^{-3}$, respectively. The strain decreased with the increase in deposition time. The TEM images indicate that the samples included cubic crystals. SEM and AFM images of both films confirm that the films had a smooth surface, strong adhesion to the substrate, and a narrow particle size distribution. The surface roughness and $S_{\text{sq}}$ increased with increasing deposition time. The optical properties of the two films, such as UV–vis and NIR transmission and reflection, band gap, and refractive index were studied and compared. The Raman study was employed to further analyze the samples. $R_\square$ and sensitivity of the films demonstrated that these values were strongly affected by the deposition time and bath composition. Our results suggest that PbS-I films as thick as 300–1000 nm could be applied to IR detectors, and that PbS-II films with thickness of 40–120 nm (reflectance up to 61%) could be used for solar control coatings.

### Table 3

Data on resistance and photosensitivity of PbS thin films.

<table>
<thead>
<tr>
<th>Film type</th>
<th>Deposition time (h)</th>
<th>Thickness (nm)</th>
<th>$R_{\square\text{D}}$ (kΩ)</th>
<th>$S$</th>
<th>$R_{\square\text{C}}$ (kΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PbS-I</td>
<td>1–4</td>
<td>300–1000</td>
<td>30–300</td>
<td>0.05–0.25</td>
<td></td>
</tr>
<tr>
<td>PbS-II</td>
<td>1–4</td>
<td>40–120</td>
<td>&gt; 2000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### References


