Molar concentration Effects on the Optical and Structural Properties of nanostructural SnO₂ Thin Films

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Abstract Thin films of nanostructured SnO₂ with different molarities were prepared by chemical spray pyrolysis technique. XRD analysis reveals that all the films were tetragonal polycrystalline with a preferred orientation along (110) plane. AFM measurements indicate that the value of the grain size for 0.05 M, 0.1 M and 0.15 M were 111nm, 78 nm and 58 nm respectively. SEM micrograph proved the existence of small cracks on the film surface, EDS confirmed the composition percentage ratio of Sn and O₂ and no trace of impurities could be detected. PL spectra gives the indication about optical energy gap and the effect of concentration on it which appeared as a blue shift. The transmittance was studied for the deposited thin films ,identifying that the transmittance decreases by the increase in molarity. The value of the optical energy gap of the deposited thin films increased upon increasing molar concentration due to quantum confinement effect. The Urbach energy was also studied, their values decrease as the molar concentration increase.

Introduction

Stannic oxide had a considerable attention due to its amazing properties like, eminent chemical stability, high transparency, low resistivity, SnO₂ is insulator in its bulk condition, while its shows a semiconductor behavior when prepared as a thin film due to the deviation from stoichiometry result as n-type semiconductor, top most infrared reflectivity, SnO₂ posses high electron mobility and wide band gap together with non toxicity and redundancy in nature[1-4]. For these reasons SnO₂ was spotlighted in many numerous applications such as potential anode in lithium ion batteries[5], solar cells[6], gas sensors[7,8], varistors[9] and photocatalysis[10]. Various experimental techniques were adopted to fabricate SnO₂ thin films depending on kind of application such as, rf sputtering[11], sol-gel[12],pulsed laser deposition[13], successive ionic layer adsorption and reaction SILAR[14], electron beam evaporation technique[15],chemical vapor deposition[16] and spray pyrolysis[17,18]. Spray pyrolysis technique was used in this work to deposit SnO₂ thin films onto quartz substrates with different concentrations and study the effect of molarity on the structural, morphological and optical properties of nanostructure SnO₂ thin films.

Experimental details

Thin films of SnO₂ have been prepared by chemical spray pyrolysis technique. Aqueous solution of SnCl₄.5H₂O with different molarities (0.05,0.1,0.15M) was used as a source of Sn, Quartz substrates were used to deposit SnO₂. After many trials, the following conditions was chosen in order to obtain homogenous films, pinhole free, well adherent to substrates. These conditions arrived at the following: substrate temperature was 500 °C and was kept constant during the deposition process, distance between substrate and nozzle was 28 cm, spraying time was 10 S lasted by 90 to obviate immoderate cooling, deposition rate was 4 ml/min. nitrogen was used as a gas carrier.

The thickness of the film was measured by gravimetric method and was in the range of 300 nm Structural properties were carried out using X-Ray Diffraction Technique (shimadzu - XRD6000, shimadzu company /Japan. Morphological properties were accomplished by Jeol JSM-6335F scanning electron microscope equipped with (EDAX). Topographical was achieved by atomic force
microscopy (AFM) Nasoscope III and Dimension 3100. Photoluminescence and the transition energy of the samples were measured using the (ELICO, SL174, spectroflurometer, Xe Lamp Power Supply). Transmittance and absorbance were measured by using a double beam spectrophotometer (Schimadzu 1650 UV probe Japan) in the wavelength range (350-1100)nm. All the measurements were achieved at room temperature.

Results and discussion

The XRD Patterns recorded for molar concentration of SnO$_2$ thin films are shown in Fig. (1). Utilizing the JCPDS data card no. 41-1445, these films were found to be of cassiterite type with a tetragonal structure. The main diffraction peaks attributed to (110), (101), (200), and (211) of SnO$_2$ these peaks indicate the polycrystallinity of these films, have a preferred orientation along (110) which remains prevalent irrespective of the molar concentration. Small peaks were shown in 0.05 M and 0.1 M and vanish when we reached 0.15 M. The lattice constant values for a$_0$ and c$_0$ were tabulated in Table 1, these values were in good agreement with the data obtained by JCPDS data card no. (41-1445). The average crystallite size was calculated using Scherrer formula for different molarties and was found to decrease as the molar concentration increase as can be seen from Table 1. Texture coefficient[19] was calculated for the deposited thin film, their values were shown in Table 1 indicating unequivocally that the preferred orientation is along(110). The number of crystallite per unit area and the dislocation density[20] were obtained also. Their values were listed in Table 1 showing increase as the concentration increased.

![XRD patterns for different molarties of SnO$_2$ thin films](image-url)

Fig. 1 XRD patterns for different molarties of SnO$_2$ thin films
Table 1 Structural parameters for different molarties of SnO$_2$ thin films

<table>
<thead>
<tr>
<th>Molarity</th>
<th>$a_0$ (Å)</th>
<th>$c_0$ (Å)</th>
<th>Strain</th>
<th>$D_{av}$ (nm)</th>
<th>$T_C$</th>
<th>No of crystallites /unit area $(\text{m}^{-2}) \times 10^{18}$</th>
<th>Dislocation density $(\text{m}^{-2}) \times 10^{16}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>4.741</td>
<td>3.190</td>
<td>-0.094</td>
<td>21</td>
<td>1.32</td>
<td>0.0378</td>
<td>0.226</td>
</tr>
<tr>
<td>0.1</td>
<td>4.767</td>
<td>3.182</td>
<td>0.156</td>
<td>6</td>
<td>1.71</td>
<td>1.6200</td>
<td>2.700</td>
</tr>
<tr>
<td>0.15</td>
<td>4.769</td>
<td>3.225</td>
<td>-1.192</td>
<td>4</td>
<td>1.51</td>
<td>5.4600</td>
<td>6.250</td>
</tr>
</tbody>
</table>

Fig. 2 depicts the AFM images (0.125 x 0.125 $\mu$m) with Granularity Cumulation Distribution Report of SnO$_2$ with a different morality grown on quartz substrate this measurement was performed near the center region of the deposited thin films. It can be seen that by increasing the molarity the grain size decrease. No mechanisms control the kinetic grain growth these are ripening and coalescence, ripening responsible for the reduction of surface to bulk ratio, while coalescence deals with the combination of two small grains with the same size to merge into larger grain[21]. AFM measurements indicated that the surface roughness and RMS roughness were smooth, the film with 0.1 M was smoother than the 0.05 M and 0.15 M. The values of roughness average, RMS roughness and grain size were listed in Table 2.

Table 2 AFM Parameters (roughness average, RMS roughness and grain size)

<table>
<thead>
<tr>
<th>Molarity</th>
<th>Roughness average (nm)</th>
<th>RMS roughness (nm)</th>
<th>Grain size (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>1.810</td>
<td>2.110</td>
<td>111</td>
</tr>
<tr>
<td>0.1</td>
<td>0.485</td>
<td>0.565</td>
<td>78</td>
</tr>
<tr>
<td>0.15</td>
<td>1.400</td>
<td>1.300</td>
<td>58</td>
</tr>
</tbody>
</table>

Fig. 3 represents the SEM micrograph of SnO$_2$ thin films with different molarity concentration prepared by spray pyrolysis. No evidence of well crystalline can be observed, these results were in good agreement with Patil et al. [22], but it can be seen that better crystallinity in comparison between the variation of molarity was presented in Fig.1-a and Fig 1-b, while Fig 1-c show small cracks on the film surface which might be due to the variation of expansion and intrinsic stress [23]. Table 3 shows the composition percentage of Oxygen and Tin, no other contribution of impurities was detected. EDS were secure to get information concerning the film composition[24]. EDS analysis disclose the oxygen/tin atomic ratio, their values were 2.597, 1.4271 and 0.792 for 0.05 M, 0.1 M, 0.15 M respectively.

Fig. 4 shows the PL spectra which were measured at room temperature of SnO$_2$ prepared with different concentrations. The peak of (0.05M) was around 320 nm is very broad and was shifted toward lower wavelength (blue shift) as the molar concentration increase due to quantum confinement effects.
Fig. 2 AFM Topography and Granularity Cumulation Distribution of SnO$_2$ with different molarties

0.05 M

0.1 M

0.15 M

Fig. 2 AFM Topography and Granularity Cumulation Distribution of SnO$_2$ with different molarties
Fig. 3 SEM photograph of different molarity for SnO$_2$ thin films (a) 0.05 M  (b)0.1M (c)0.15M

Table 3 EDS contribution of SnO$_2$ with different molar concentration

<table>
<thead>
<tr>
<th>Molarity</th>
<th>Oxygen %</th>
<th>Tin %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>66.93</td>
<td>25.77</td>
</tr>
<tr>
<td>0.10</td>
<td>58.80</td>
<td>41.20</td>
</tr>
<tr>
<td>0.15</td>
<td>44.19</td>
<td>55.81</td>
</tr>
</tbody>
</table>
The optical transmittance spectra of SnO$_2$ prepared with different molar concentration were shown in Fig 5. From this figure, it can be recognized that the increase in molar concentration has scored in a decrease in transmittance. A decrease in the transmittance of SnO$_2$ thin film might be due to an increase in light scattering by defect on the surface of the film, the surface of the thin film creates a defect state with oxygen deficiencies which reduce the crystal size[24,25]. The average transmittance at 550 nm was 66.77, 62.89,49.18 for 0.05 M,0.1 M and 0.15 M respectively.
Fig. 6 depicts the relation between the absorbance and wavelength, it can be seen that there is a shift in the absorption edge toward shorter wavelengths (blue shift) this blue shift can be attributed to the quantum confinement\[26,27\]. It has been believed that the absorbance is molarity dependence. The value of the optical energy gap can be estimated by Tauc formula \[28\] according to the following relation

\[
(\alpha hu) = A (hu - E_g)^r
\]  
\[1\]

Where \( \alpha \) represent the absorption coefficient, \( hu \) is the photon energy, \( E_g \) is the optical energy gap, while \( A \) is constant which depends on reduced mass, refractive index and speed of light\[29\]. As we observe that SnO\(_2\) thin film was exist in tetragonal structure only and because of the sharpness of the absorption edge which shows linearity against energy for the as deposited films\[30\]. The extrapolation of the linear part can be useful in determining the optical energy gap as shown in Fig. 7, the value of the optical energy gap was estimated to be increased as the concentration increase because of the quantum confinement effect. This behavior is in good agreement with Varnamkhasti \textit{et al.}\[31\].

![Fig. 6 Absorbance versus wavelength for the as deposited thin films](image-url)
The value of Urbach tail of the SnO$_2$ thin films can be estimated from the known relation [32]:

$$\alpha = \alpha_0 \exp \left( \frac{E}{E_U} \right)$$  \hspace{1cm} (2)

Where $E_U$ represents the width of the exponential absorption edge, $E$ is the photon energy, and $\alpha_0$ is constant. Fig 8 shows the relation between $\ln(\alpha)$ as a function of photon energy, so the Yrbach energy was calculated from the inverse of the slope, it can be seen from the results that $E_U$ decreases with increase of concentration, showing an inverse relation with the optical energy gap. These results were in good agreement with Rahal et al. [33].
Conclusions
The effect of different molar concentration was studied successfully. XRD analyses show that all deposited thin films were polycrystalline. The average crystallite size obtained by Scherrer formula gave an indication about the location of nanostructure. AFM micrograph confirm the existence of nanostructure with a value that decrease as the molar concentration increase. The optical energy gap was estimated showing an increase in its value as the molar concentration increase and this because of the quantum confinement effect.
References


