CHAPTER - V

OPTICAL AND ELECTRICAL PROPERTIES

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CHAPTER- V
OPTICAL AND ELECTRICAL PROPERTIES

5.1 INTRODUCTION

A detailed investigation on the optical and electrical properties of semiconductor materials both in bulk and in thin film form becomes essential for their effective application in optoelectronic devices, solar cells etc. The absorption of energy by semiconductors enhances transport of charge carriers and its absorbed energy delivered to the external loads. A careful study on the optical and transport properties of the semiconductors synthesized by various techniques is therefore necessary. In recent years lot of interest has been shown on transition metal dichalcogenide compounds (TMDC) like MX$_2$ (M = Mo, W ; X = S, Se) [1]. The layered semiconductors are of interest in solar energy conversion due to the ingenuous arrangement of structural lattice with cations and anions [2]. These single crystals and thin films have selective properties like band gap in the range 1.0 - 2.0 eV, high optical absorption, the layered type of arrangement between the cations, all of which make this material an important one in the photoelectrochemical conversion and photovoltaic [3].

5.2. OPTICAL PROPERTIES OF Mo$_x$W$_{1-x}$Se$_2$ (0 ≤ X ≤ 1) FILMS

5.2.1. Review on Mo$_x$W$_{1-x}$Se$_2$ Films

Pouzet et al.[4] have done the optical measurements at liquid nitrogen temperature. The transmission spectrum for a synthesized layer, sputtered layer
and for a single crystal of MoSe₂. The single crystal spectrum shows well resolved peaks while MoSe₂ thin films show small and broad peaks. Sputtered MoSe₂ layers show only a peak for the exciton A and then saturation when the photon energy increases. Goldberg et al. [5] have reported that the energy gap of MoSe₂ monocrystals varies between 1.00 and 1.17 eV. MoSe₂ being a layered indirect band gap semiconductor, the value of \( n \) depends on the density of states. The two extreme cases of the density of states are isotropic and bidimensional for \( n = 2 \) and \( n = 1 \) respectively. In real situations, generally [6] \( 1 \leq n \leq 2 \). The optical band gap of the MoSe₂ films was determined to be 1.15 eV and 1.26 eV by extrapolating the straight lines of \( \alpha^{1/2} \) versus \( E \) and \( \alpha \) versus \( E \) respectively [7].

Anand et al. [8] have reported the indirect band gap value of 1.17 eV for an electrodeposited thin film from the optical absorption spectra. The optical studies showed that MoSe₂ thin film was an indirect band gap material with band gap 1.14 eV. The weak absorption in samples is because of the small thickness of the film with the composition. Broadening of the peak is expected because of the polycrystallinity and non-uniformity of the electrodeposited film [9].

A pronounced absorption edge was evident in the vicinity of 600 – 800 nm from the absorption spectra. The allowed direct band gap was calculated as 1.46 eV[10]. The optical indirect band gap of r.f. sputtered WSe₂ films was determined to be 1.12 eV for (direct) and 1.25 eV for (indirect) transitions [11]. The MoSe₂ and WSe₂ single crystals were prepared by bromine transport from the gas phase.
The variation of refractive index with wavelength $\lambda$ in the near absorption edge was studied and reflectivity measurements were also reported [13]. For an electrodeposited WSe$_2$ film from optical absorption spectrum the direct band gap $= 0.98$ eV and the indirect band gap $= 1.10$ eV. For WSe$_2$ single crystals the direct band gap $= 1.16 \pm 0.03$ eV. This slight difference in the two values is expected because of the non-uniformity and defective nature of the WSe$_2$ thin films [14]. Both for n-type and p-type WSe$_2$ single crystals grown by chemical vapour transport technique in the wavelength region from 900 - 1150 nm the variation in refractive index was analyzed and reported from transmissivity and reflectivity measurements. Similarly in the wavelength range between 800 and 900 nm the variation of absorption coefficient $\alpha$ was discussed, and the band gap reported is 1.35 eV [15,16]. A review of layer type tungsten dichalcogenide compounds, their preparation, structure, properties and uses was written by Srivastava and Avasthi. In this again they have reported the band gap values of WSe$_2$ single crystals and thin films prepared by various methods with the approximate determination of $E_g$ for the mixed cation crystals $= 1.3$ to 1.4 eV [17].

In the present work, the optical properties of pulse plated MoSe$_2$, WSe$_2$ and Mo$_x$W$_{1-x}$Se$_2$ ($x = \frac{1}{4}, \frac{1}{2}, \frac{3}{4}$) thin films are studied. For optical measurements in all the above cases thin films were deposited over F:SnO$_2$ coated glass substrates for a time of deposition of 10 minutes only. The following studies are carried out: (a) the band gap of pulse plated MoSe$_2$, (b) WSe$_2$ and
thin films is measured; (d) the optical constants of refractive index 'n', and extinction coefficient 'k', are evaluated.

5.2.2. Band gap Evaluation

(i) From Optical Absorption Studies

Semiconductors with controlled band gap are of immense interest due to their application in optoelectronic devices and photoelectrochemical solar cell fabrication. The semiconducting films, Mo$_x$W$_{1-x}$Se$_2$ is used for optical measurements, which are coated on F:SnO$_2$ coated glass plates. The glass slide coated with conducting tin oxide (SnO$_2$) has a sheet resistance of 20 $\Omega$ / cm$^2$ and its thickness is 0.1 $\mu$m. It has been assumed that the film thickness of F:SnO$_2$ is negligible when compared with semiconductor thickness (> 0.5 $\mu$m). The absorption and transmission properties are studied using double beam spectrophotometer and these spectra are used to calculate their band gap variations. A plot of $(\alpha h\nu)^{1/2}$ versus $h\nu$ yielded a straight line and the intercept of the plot yielded band gap value of the film.

5.2.3 MoSe$_2$ Films

The transition metal dichalcogenides were usually indirect band gap semiconductors. In the present study the optical absorption measurements near the fundamental edge with the aim of estimating the band gap of pulsed electrodeposited MoSe$_2$ films. Absorption spectra can be taken using spectrophotometers in the wavelength region 400 nm to 1100 nm as shown in
The fundamental dependence of the absorption coefficient $\alpha$ at different energies can be expressed by

$$\alpha = \frac{[K(E-E_g)^n]}{E}$$

where $K$ is a constant, and $n = 1/2$, $3/2$ and $2$ respectively for direct allowed, direct forbidden and indirect allowed transitions. The value of $n$ also depends on the shape of the density of states. The optical band gap of the MoSe$_2$ films was determined by extrapolating the straight line portion of the graph $(\alpha h\nu)^{1/2}$ versus $h\nu$ and is shown in Fig.5.2. The indirect band gap of MoSe$_2$ film was 1.16 eV, which is in close agreement with Earlier reported value of 1.14 eV for the electrodeposited film [18].

### 5.2.4 WSe$_2$ Films

The variation of optical absorption with wavelength for a WSe$_2$ film is shown in Fig.5.3. The figure shows a constant absorption behaviour up to about 600 nm and then starts increasing. The absorbance data is used to obtain the band gap for WSe$_2$ films. From Fig.5.4 the band gap is estimated as 1.42 eV at 300 K. This value is in excellent agreement with the earlier reported value of 1.435 eV for the electrodeposited film [19 - 22].

### 5.2.5 Mo$_x$W$_{1-x}$Se$_2$ ($x = \frac{1}{4}, \frac{1}{2}, \frac{3}{4}$) films

The optical absorption studies have been carried out for the pulsed electrodeposited Mo$_x$W$_{1-x}$Se$_2$ films. The absorption spectra for the
Fig. 5.1: Variation of optical absorption with wavelength for the pulse deposited MoSe$_2$ film
Fig 5.2. \((\alpha h\nu)^{1/2}\) versus \(h\nu\) for pulse deposited MoSe\(_2\) film.
Fig 5.3. Variation of optical absorption with wavelength for the deposited WSe$_2$ film.
Fig 5.4. $(\alpha h\nu)^{1/2}$ versus $h\nu$ for pulse deposited WSe$_2$ film
electrodeposited $\text{Mo}_x\text{W}_{1-x}\text{Se}_2$ ($x = \frac{1}{4}, \frac{1}{2}, \frac{3}{4}$) films are shown in Fig. 5.5, 5.6 and 5.7 respectively. The band gap values calculated are 1.30 eV, 1.25 eV and 1.53 eV respectively and the corresponding band gap diagrams are shown in Fig. 5.8, 5.9 and 5.10 respectively, which is the first ever reported value for $\text{Mo}_x\text{W}_{1-x}\text{Se}_2$ ($x = \frac{1}{4}, \frac{1}{2}, \frac{3}{4}$) thin film form.

5.3 EVALUATION OF OPTICAL CONSTANTS

The estimation of optical constants for semiconducting thin films prepared under variety of techniques is a vital field in the materials research [23]. The optical matching of refractive index reduces reflection losses and enhances transmission and hence increases the efficiency of optoelectronic devices. From the optical spectra, the refractive index ($n$) and the extinction coefficient ($k$), are determined. For determining the optical constants, a modified continuous differential descent method is used and is already described in chapter II.

5.3.1 MoSe$_2$ Films

The dispersion of ‘$n$’ and ‘$k$’ for different wavelengths obtained using the CDD algorithm for pulsed electrodeposited MoSe$_2$ films is shown in Fig. 5.11. In the near absorption edge, the refractive index ‘$n$’ value reaches 3.55 and then reaches a maximum of about 3.85. Initially from wavelength 400 to 800 nm the variation is a sinusoidal one. The extinction coefficient ‘$k$’ varies from $0.58 \times 10^{-7}$ to $0.11 \times 10^{-3}$ as the wavelength is decreased from 1200 nm to 400 nm. For MoSe$_2$ single crystals the $n$ value reported is 4.25 [24].
Fig 5.5. Variation of optical absorption with wavelength for the electrodeposited $\text{Mo}_{0.25}\text{W}_{0.75}\text{Se}_2$ thin film
Fig 5.6. Variation of optical absorption with wavelength for the electrodeposited \( \text{Mo}_0.5\text{W}_0.5\text{Se}_2 \) thin film
Fig 5.7. Variation of optical absorption with wavelength for the electrodeposited $\text{Mo}_{0.75} \text{W}_{0.25}\text{Se}_2$ thin film
Fig 5.8 $\left(\frac{\alpha h}{\nu}\right)^{1/2}$ versus $h\nu$ plot for Mo$_{0.2}$W$_{0.76}$Se$_2$ thin film.
Fig 5.9: $(\alpha h \nu)^{1/2}$ versus $h \nu$ plot for $Mo_0.5W_0.5Se_2$ film
Fig 5.10: $(\alpha \beta \gamma)^{1/2}$ versus $h\nu$ plot for $M_{0.75}W_{0.25}Se_{2}$ film.
Fig 5.11 $n$ and $k$ versus $\lambda$ for MoSe$_2$ thin film
5.3.2 WSe$_2$ Films

The dispersion of $n$ and $k$ with wavelength is shown in Fig.5.12. The value of refractive index starts increasing gradually near 500 nm which corresponds to the absorption edge of WSe$_2$. The evaluated value of refractive index is greater than that of the MoSe$_2$ thin film. The value of ‘k’ varies from 0.57 x $10^{-9}$ to 0.98 x $10^{-3}$ as the wavelength changes from 1200 nm to 400 nm. The ‘k’ values are very low revealing the very thin nature of the pulsed electrodeposited WSe$_2$ films.

This is supported by the high transmittance values and lower absorption values reported earlier in Fig.5.11 and Fig.5.12. The ‘n’ values are high of about 3.90 below the absorption edge and is about 3.0 at the absorption region which is located at 1050 nm for WSe$_2$ films. This value is close to the ‘n’ value of 2.84 for WSe$_2$ single crystal [25].

5.3.3 Mo$_{0.5}$W$_{0.5}$Se$_2$ Film

The variation of the values of ‘n’ and ‘k’ for the pulse electrodeposited Mo$_{0.5}$W$_{0.5}$Se$_2$ film is shown in Fig.5.13. The ‘n’ values vary in the range of 2.75 - 3.92, which shows the same trend as MoSe$_2$ and WSe$_2$. The increasing trend of ‘n’ starts at about 400 nm, which coincides with the absorption edge value already reported in the previous section. The ‘k’ values are very low in the order of about 0.50 x $10^{-5}$. 

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5.4 ELECTRICAL PROPERTIES

The studies on the transport properties of MoSe$_2$ and WSe$_2$ have attracted attention due to their high potentials in photoelectrochemical cells. The electrical properties of MoSe$_2$ and WSe$_2$ have been studied by several researchers [17-26]. However, thin film based on Mo$_x$W$_{1-x}$Se$_2$ has not been studied in detail with respect to their electrical properties. The electrical properties of this system is found to depend on the various deposition parameters i.e., bath pH, temperature, molarity of the constituent species and annealing conditions of the films. Hence, a study of electrical conductivity of these alloy films is an important aspect.

The present study deals mainly with the electrical conductivity of these films and their related semiconductor parameters.

5.4.1 Review on Mo$_x$W$_{1-x}$Se$_2$ Films

The electrical properties of MoSe$_2$ films deposited by pulse electrodeposition technique cathodically on titanium substrate from an ammoniacal solution of H$_2$MoO$_4$ and SeO$_2$ under galvanostatic conditions [17]. The film deposited on titanium substrate was used for electrical conductivity measurements. Forward and backward I-V characteristics were found to be similar, indicating an ohmic contact. Electrical resistivities at different temperatures were calculated from the DC voltage and current measurements in the region where the I-V characteristic was linear. The resistivity $\rho$ increases with
increase of temperature. Molybdenum diselenide were synthesized at 1273 K for 24 h. The temperature dependence of electrical conductivity of compressed samples $1.85 \leq \text{Se} / \text{Mo} \leq 2.0$ was discussed [18]. Molybdenum diselenide thin films were synthesized on molybdenum substrates [19]. The electrical resistance is governed by hopping conduction in the low temperature range (80 – 500 K) and by grain boundary scattering mechanisms at higher temperatures. At low temperatures, below 250 K, a very low activation energy of 40 meV is observed, which might be caused by hopping conduction [20-22].

The optical and electrical properties of MoSe$_2$ films synthesized by solid-state reaction from thin films [4]. The physical parameters of MoSe$_2$ deduced from electrical measurements are (1) electrical conductivity $\sigma \Omega^{-1} \text{cm}^{-1}$ (2) $qV$ eV (3) band gap $E_g$ eV. The structure, the chemical composition, the morphology, the optical band gap and the variation of resistivity with the temperature of the MoSe$_2$ thin films prepared by d.c. diode sputtering are presented [7]. The room temperature resistivity of the films varied from $0.1 \times 10^3$ to $15 \times 10^3 \Omega \cdot \text{cm}$; it increased when the grain size of the film decreased, or the crystallite order decreased. In the range 500-550 K the resistivity follows the Arrhenius dependence with temperature; the activation energy $\Delta E = 0.57$ eV.

The electrical conductivity and Hall coefficient perpendicular to the c-axis of hexagonal MoSe$_2$ and WSe$_2$ are measured over the temperature ranges 120 to 1170 K and 140 to 820 K respectively. Carrier mobility measurements appear to show the intermediate conductivity region is a result of the temperature
dependent carrier mobility rather than the exhaustion of transitions from impurity levels. These observations, together with the consistent values for the activation energies of conduction, suggest that over the entire temperature range the measured conductivities are the result of intrinsic processes in the crystal [26]. By chemical vapour transport single crystals of (Mo / W) Se$_2$ were prepared in stoichiometric condition. The electrical conductivity $\sigma$, carrier concentration $p$ and Hall mobility $\mu$ at 300 K and activation energy $E_a$ of as doped single crystals were reported [27]. Molenda et.al have reported the activation energy $E_a$ of electrical conductivity as a function of non-stoichiometry of tungsten diselenide [29]. For a r.f. sputtered tungsten foil the resistivity varied from 10 to 100 $\Omega$-cm. The temperature dependences of electrical resistivity and conductivity from 80 to 500 K are plotted. In the temperature region above 250 K, since the studied films are polycrystalline, grain boundary theories may have to be taken into account [28 - 30]. The estimated barrier height at the grain boundary was about 0.2 eV [31]. Measurements of transmissivity-reflectivity, photocurrent, Hall effect and electron beam induced current were carried out [32,33]. A review on layer type tungsten dichalcogenide compounds: their preparation, structure, properties and uses were written by Srivastava et.al [34]. The carrier type, resistivity ($\Omega$-cm) Hall coefficient $R_H$ (cm$^3$ coulomb$^{-1}$), carrier concentration $n$ (cm$^{-3}$), Hall mobility $\mu$ (cm$^2$V$^{-1}$sec$^{-1}$) and Seebeck coefficient $S$ (mkV$^0$C$^{-1}$) were reported by various workers. WSe$_2$ film, electrodeposited on titanium substrate was used for electrical studies. From $p$ versus $1/T$ plot electronic mobility at room temperature was calculated using the relation $\mu_e = 1/\rho = 1.55$ cm$^2$V$^{-1}$s$^{-1}$. Further, the
temperature dependent electronic mobility can be calculated from the plot of \( \log \rho \) and \( \log T \), using the expression \( \mu_e \sim (1/T)^m \sim (1/T)^{1.7} \) where \( m \) is the slope of that plot [14].

Single crystals of (Mo/W)Se\(_2\) were used for anisotropy ratio \( \nu \), it varies with temperature as \( \nu = A e^{E_i/kT} \). Another plot of log \( V \) versus 1/T was also studied. From the slope of this plot the activation energies are calculated form the slopes for various crystal composition [34]. The electrical resistivity of the single crystal solid solutions Mo\(_x\)W\(_{1-x}\)Se\(_2\) (0 \( \leq x \leq 1 \)), grown by direct vapour transport technique is studied in the temperature range from 300 to 600 K. The room temperature values of resistivity are 1.43 \( \Omega \)-cm for p-type 2H-WSe\(_2\) and 2.36 \( \Omega \)-cm for p-type 2H-MoS\(_2\). The study reveals that the crystals are intrinsic semiconductors in the temperature range of investigation [35].

As there are no reports available on Mo\(_x\)W\(_{1-x}\)Se\(_2\) in thin film form the electrical properties of these films prepared by pulse electrodeposition are reported for the first time.

5.4.2 Studies on Electrical Properties

The electrical properties of molybdenum tungsten dichalcogenides (MoSe\(_2\), WSe\(_2\) and Mo\(_x\)W\(_{1-x}\)Se\(_2\) (\( x = \frac{1}{4}, \frac{1}{2}, \frac{3}{4} \)) prepared by pulse deposition technique are studied in vacuum of 10\(^{-4}\) torr. The current-voltage characteristics are studied in the temperature range 303 - 623 K. The temperature is measured using calibrated chromel - alumel thermocouple.
The electrical characterization of pulse deposited semiconducting films by resistance measurements is complicated by the fact that the film must be removed from the conducting substrate without damage prior to any measurement.

The chalcogenide films are removed from the conducting substrate by attaching a plate to the surface of the film using an epoxy. After the epoxy is dried for ten hours, the epoxy and the molybdenum tungsten dichalcogenide film comes away with the plate when force is applied between the plate and the substrate. Crack and pinhole free films of area 0.5 to 1.0 cm\(^2\) are removed from tin oxide coated glass substrates. Thickness of typical films used for the electrical studies are in the range of 1.4 to 2.0 \(\mu\)m. Contacts to the semiconductor films are made with silver paste to obtain low resistance ohmic contacts [36]. The current-voltage characteristics show a linear behaviour suggesting that silver paint forms ohmic contact to Mo\(_x\)W\(_{1-x}\)Se\(_2\) films.

### 5.4.3 MoSe\(_2\) Films

The effect of temperature on electrical resistivity \(\rho\) of the film was studied by varying the temperature of the film from 303 to 623 K, while doing so the resistivity was decreased from 1.31x10\(^4\) \(\Omega\)-cm to 0.176 x 10\(^4\)\(\Omega\)-cm for the duty cycle of 30\%. The temperature dependence of the electrical resistivity from 303 to 623 K was shown in Fig.5.14. By plotting ln \(\sigma\) versus 1/T, the activation energy \(E_a\) was calculated using the relation for the optimized pulse plated thin film.
Fig 5.14. Variation of $\rho$ with inverse absolute temperature for the pulse plated MoSe$_2$ film.
\[ \sigma = \sigma_0 \exp\left(-\frac{E_a}{kT}\right) \]  

(5.3)

The electrical conductivity was studied for films deposited at different duty cycles and the activation energies \( (E_a) \) are calculated and are in agreement with the earlier reported values 0.57 eV to 1.10 eV reported in \([37]\). From the plot of \( \ln(\sigma T^{-1}) \) versus \( 1/T \) the trapped energy state \( (e_i) \) was calculated using the relation

\[ \sigma \propto T \exp\left[\frac{(E_a + e_i)}{kT}\right] \]  

(5.4)

and are given. By taking \( \ln(\sigma T^{1/2}) \) versus \( 1/T \), the barrier height \( \phi_B \) was calculated using the relation

\[ \sigma \propto T^{1/2} \exp\left(-\frac{\phi_B}{kT}\right) \]  

(5.5)

where \( N \) being the acceptor concentration

\( N^* \) - exists for which grains are only partially depleted \( (2W < d, d \text{ being the grain size}) \)

\( W \) – Width of the depletion region

\( k \) – Boltzmann constant

\( T \) – Absolute temperature in Kelvin unit

and are tabulated in Table 5.1 and is in close agreement with the earlier reported value 0.15 eV \([35]\). All these plots are shown in Fig. 5.15, 5.16 and 5.17 say 10, 20, 30, 40 and 50 percentages were studied. The variation of electrical resistivity \( \rho \) with \( 1/T \) is shown in Fig 5.14. It is obvious from Fig 5.14 that the conductivity \( \sigma \) increases with the increase of temperature, which is the characteristic of impurity conduction. The increase in conductivity is due to the decrease in mobility.
### Table - 5.1
**Electrical parameters for MoSe₂ films**

<table>
<thead>
<tr>
<th>Duty Cycle %</th>
<th>Activation Energy $E_a$ in eV</th>
<th>Trapped energy State $e_t$ in eV</th>
<th>Barrier height $\phi_B$ in eV</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.86</td>
<td>0.365</td>
<td>0.123</td>
</tr>
<tr>
<td>20</td>
<td>0.71</td>
<td>0.201</td>
<td>0.130</td>
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<tr>
<td>30</td>
<td>0.86</td>
<td>0.365</td>
<td>0.162</td>
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<tr>
<td>40</td>
<td>0.71</td>
<td>0.201</td>
<td>0.110</td>
</tr>
<tr>
<td>50</td>
<td>0.71</td>
<td>0.201</td>
<td>0.110</td>
</tr>
</tbody>
</table>
Fig 5.15. Variation of $\ln(\sigma)$ with inverse absolute temperature for pulse plated MoSe$_2$ film
Fig 5.16. Variation of \( \ln(\sigma T^{-1}) \) with inverse absolute temperature for pulse plated MoSe\(_2\) film.
Fig 5.17. Variation of \( \ln(\sigma T^{1/2}) \) with inverse absolute temperature for pulse plated MoSe\(_2\) film.
caused by scattering of charge carriers from ionized impurity centres. From this as the temperature increases the electrical resistivity was found to decrease. By drawing plots (i) \( \ln \sigma \) versus \( 1/T \) (ii) \( \ln (\sigma T^{-1}) \) versus \( 1/T \) (iii) \( \ln \sigma T^{1/2} \) versus \( 1/T \) the activation energy \( E_a \), trapped energy state \( e \), and barrier height \( \varphi_B \) are calculated using the above three equation (5.3), (5.4) and (5.5) [29] for films deposited at different duty cycles and are tabulated in Table 5.2 and the corresponding plots are shown in Fig.5.15, 5.16 and 5.17.

### 5.4.4 WSe₂ Films

The temperature dependence of the electrical resistance between 303 K and 623 K for pulse plated WSe₂ thin films prepared at different duty cycles. From the plots Fig.5.18, 5.19, 5.20 and 5.21, the activation energy \( E_a \), trapped energy state \( e \), and the barrier height \( \varphi_B \) are calculated and tabulated in Table 5.2.

The activation energy calculated was in agreement with the earlier reported values 0.57 eV to 1.10 eV and the barrier height 0.15 eV, which is again comparable with the reported value [4].

### 5.4.5 MoₓW₁ₓSe₂ Films

The variation of electrical resistivity \( \rho \) at different temperature from 303 to 623 K for MoₓW₁ₓSe₂ (\( x = \frac{1}{4}, \frac{1}{2}, \frac{3}{4} \)) films is estimated and represented in
Fig 5.18. Variation of $\rho$ with inverse absolute temperature for the pulse plated WSe$_2$ film
Fig. 5.19. Variation of $\ln(\sigma)$ versus inverse absolute temperature for the pulse plated WSe$_2$ film
Fig. 5.20. Variation of $\ln(\sigma T^{-1})$ versus inverse absolute temperature for pulse plated WSe$_2$ film
Fig 5.21. Variation of $\ln(\sigma T^{1/2})$ versus inverse absolute temperature for pulse plated WSe$_2$ film.
Table - 5.2

Electrical parameters of the WSe$_2$ films

<table>
<thead>
<tr>
<th>Duty Cycle %</th>
<th>Activation Energy $E_a$ in eV</th>
<th>Trapped energy State $e_t$ in eV</th>
<th>Barrier height $\varphi_B$ in eV</th>
</tr>
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<tbody>
<tr>
<td>10</td>
<td>0.96</td>
<td>0.6502</td>
<td>0.120</td>
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<tr>
<td>20</td>
<td>0.90</td>
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<td>30</td>
<td>0.86</td>
<td>0.6622</td>
<td>0.115</td>
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<td>0.86</td>
<td>0.6524</td>
<td>0.110</td>
</tr>
<tr>
<td>50</td>
<td>0.72</td>
<td>0.6405</td>
<td>0.130</td>
</tr>
</tbody>
</table>
Fig. 5.22 for the pulse electrodeposited films. It is found that the resistivity of the films varies linearly with composition in the range 0.5 to 54000 Ω-cm.

By drawing plots (i) ln σ versus 1/T (ii) ln (σT⁻¹) versus 1/T (iii) ln σT¹/² versus 1/T the activation energy Eₐ, trapped energy state e, and barrier height \( \psi_B \) are calculated using equations (5.3), (5.4) and (5.5) for films pulsed electrodeposited with different composition and the plots are shown in Fig. 5.22, 5.23, 5.24 and 5.25 respectively.

Table 5.3 shows the electrical parameters for three compositions of MoₓW₁₋ₓSe₂ \( (x = \frac{1}{4}, \frac{1}{2}, \frac{3}{4}) \) films. It has been found from hot probe studies that the MoₓW₁₋ₓSe₂ films prepared by pulse electrodeposition technique exhibited p-type nature of semiconductors. Again it was confirmed by Mott-Schottky plot also. In all the three cases the variation of resistivity with inverse absolute temperature is linear. But the order of resistivity is almost same for compositions Mo₀.₂₅W₀.₇₅Se₂ and Mo₀.₅W₀.₅Se₂. But in the case of Mo₀.₇₅W₀.₂₅Se₂ the resistivity is very low, this may be because of the incorporation of more Mo in the film.

5.5 SUMMARY AND CONCLUSION

The optical and electrical properties of MoₓW₁₋ₓSe₂ \( (x = 0, \frac{1}{4}, \frac{1}{2}, \frac{3}{4} \) and 1) films are studied. The optical constants n and k estimated using a modified continuous differential decent method and their variation with wavelength are studied. Electrical properties of MoSe₂, WSe₂ and MoₓW₁₋ₓSe₂ \( (x = \frac{1}{4}, \frac{1}{2} \) and \( \frac{3}{4} \) films are studied in the temperature range 303 to 623 K. It is found that the
Fig. 5.22. Variation of $\rho$ with inverse absolute temperature for the pulse electrodeposited $Mo_xW_{1-x}Se_2$ film.
Fig. 5.23. Variation of $\ln(\sigma)$ versus inverse absolute temperature for the pulse electrodeposited $\text{Mo}_x\text{W}_{1-x}\text{Se}_2$ film.
Fig. 5.24. Variation of $\ln (\sigma T^{-1})$ versus $(10^3/T) K^{-1}$ inverse absolute temperature for pulse electrodeposited Mo,W$_{1-x}$Se$_2$ film
Fig. 5.25. Variation of $\ln(\sigma T^{1/2})$ versus $(10^3/T)$ K$^{-1}$ for pulse electrodeposited $\text{Mo}_{0.25}\text{W}_{0.75}\text{Se}_2$ film
Table 5.3
Electrical parameters of the Mo$_x$W$_{1-x}$Se$_2$ ($x = \frac{1}{4}, \frac{1}{2}, \frac{3}{4}$) films.

<table>
<thead>
<tr>
<th>Composition</th>
<th>Activation Energy $E_a$ in eV</th>
<th>Trapped energy state $e_t$ in eV</th>
<th>Barrier height $\phi_B$ in eV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mo$<em>{0.25}$W$</em>{0.75}$Se$_2$</td>
<td>0.10</td>
<td>0.11</td>
<td>0.86</td>
</tr>
<tr>
<td>Mo$<em>{0.5}$W$</em>{0.5}$Se$_2$</td>
<td>0.07</td>
<td>0.13</td>
<td>0.91</td>
</tr>
<tr>
<td>Mo$<em>{0.75}$W$</em>{0.25}$Se$_2$</td>
<td>0.06</td>
<td>0.67</td>
<td>1.18</td>
</tr>
</tbody>
</table>
conductivity of the film varies linearly with composition. The exact value of the conductivity depends on the solid solution film composition. As the percentage of W in Mo$_x$W$_{1-x}$Se$_2$ ($x = \frac{1}{4}, \frac{1}{2}, \frac{3}{4}$) film is increased, the film resistance also increases due to the incorporation of more Se in the film. The conductivity values are in the intermediate range of the end components, which confirm the solid solution formation. Thermal activation energies, trapped energy state and barrier height of the films are estimated and the values are tabulated in Table 5.1 - Table 5.3.
REFERENCES


