10-1994

Low Cost Schottky Barrier Solar Cells Fabricated on CdSe and Sb$_2$S$_3$ Films Chemically Deposited with Silicotungstic Acid

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http://dx.doi.org/10.1149/1.2059248
http://jes.ecsdil.org/content/141/10/2871.abstract

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protons, coupled with the high mobility of hydrogen or protons in oxides.\textsuperscript{4}

Conclusion

Amorphous electrochromic niobium oxide thin films can be prepared by CVD at 350° C using niobium(V) ethoxide as a source material. Reduction and oxidation of these films in a 0.1 M Na\textsubscript{2}CO\textsubscript{3} + 0.1 M NaHCO\textsubscript{3} buffer solution resulted in desirable changes in optical absorption. Coulometry experiments indicated that the coloration efficiency of the amorphous film was 160 cm\textsuperscript{2} C\textsuperscript{−1} which is much higher than for the film prepared by a radio-frequency magnetron sputtering method suggesting that low temperature CVD offers an attractive way of preparing electrochromic Nb\textsubscript{2}O\textsubscript{5} films.

Acknowledgment

This work was supported by the Ookura Foundation. Manuscript submitted March 17, 1994; revised manuscript received May 26, 1994.

Low Cost Schottky Barrier Solar Cells Fabricated on CdSe and Sb\textsubscript{2}S\textsubscript{3} Films Chemically Deposited with Silicotungstic Acid

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Abstract

A novel method for fabricating high efficiency metal (Pt, Au, and Ni)/(CdSe or Sb\textsubscript{2}S\textsubscript{3}) Schottky barrier solar cells is reported. The method is based on the fabrication of n-CdSe or Sb\textsubscript{2}S\textsubscript{3} thin films chemically deposited with and without silicotungstic acid (STA). The performances of the Schottky junctions fabricated with the films deposited with STA, CdSe(STA), or Sb\textsubscript{2}S\textsubscript{3}(STA), are significantly higher than those deposited without STA. Under AM1 illumination, the photovoltaic properties of the improved Pt/CdSe(STA) diode showed \( V_{oc} = 0.72 \) V, \( J_{sc} = 14.1 \) mA/cm\textsuperscript{2}, \( FF = 0.70 \), and efficiency \( \eta \approx 7.2\% \). Analogous results are obtained on Pt/n-Sb\textsubscript{2}S\textsubscript{3}(STA), where the photovoltaic response of the improved diode showed \( V_{oc} = 0.63 \) V, \( J_{sc} = 11.3 \) mA/cm\textsuperscript{2}, \( FF = 0.63 \), and \( \eta \approx 5.5\% \). The ideality factor \( n \) and saturation current density \( J_0 \) were also significantly improved. C-V measurements at 1 MHz showed that the barrier height \( \phi_b \) of the fabricated diode were 0.82 and 0.59 eV for Pt/CdSe and Pt/Sb\textsubscript{2}S\textsubscript{3} junctions, respectively, and 0.81 and 0.80 eV for Pt/CdSe(STA) and Pt/Sb\textsubscript{2}S\textsubscript{3}(STA) junctions, respectively. It is also observed that the \( J_0 \) values are independent of the metal work functions (W). This is attributed to the Fermi level pinning of CdSe or Sb\textsubscript{2}S\textsubscript{3} films deposited with and without STA.

The diode ideality factor \( n \) and the saturation current density \( J_0 \) are probably the most important parameters in Schottky diode solar cells. The classical relationship of the \( J-V \) characteristics of the diodes is given by

\[
J = J_0 \left( \frac{qV}{nkT} \right)^n - 1
\]

where \( n \) is the diode ideality factor. For an ideal Schottky barrier, \( n \) equals 1, and the dark saturation current density \( J_0 \) is given by

\[
J_0 = A^* T^2 \exp \left( -\frac{q\phi_b}{kT} \right)
\]

where \( A^* \) is the Richardson constant and \( \phi_b \) is the barrier height which depends on the bandgap \( (E_g) \), the electron affinity \( \chi \) of the semiconductor, the metal work function \( (W_m) \), and the diode interface state density and distribution. Therefore, for a given semiconductor, the variation of \( \phi_b \) with \( W_m \) may indicate interface behavior due to the presence of interface states. Consequently, modification of the semiconductor may give information on the change in barrier height. Considerable effort has been expended recently in trying to understand the properties of the Schottky barrier height \( \phi_b \) in an attempt to increase the open-circuit voltage \( V_{oc} \) of solar cells.

* Electrochemical Society Active Member.

REFERENCES


Kyoto University assisted in meeting the publication costs of this article.
Among the metal sulfides, antimony trisulfide is particularly well-suited to serve as a target material for TV cameras, microwave devices, switching devices, and various optoelectronic devices.  

The films were prepared by a vacuum evaporation technique using powdered Sb$_2$S$_3$ compounds as the starting material. This causes some departures in the stoichiometry of the deposited film which are mainly due to differences in the vapor pressures of the constituents at the deposition temperature. CdSe is a promising semiconductor material for solar cells and various optoelectronic devices, with a bandgap of 1.7 eV. Photoelectrochemical (PEC) solar cells with single-crystal n-CdSe photoanodes have been studied and an efficiency of 7 to 8% obtained. It has been indicated that with appropriate electrolyte modification, the PEC efficiency of n-CdSe single crystals can be improved (~16%). Moreover, the high cost of single-crystal electrodes, which is one of the most limiting factors for their large-area fabrication, can be avoided easily by replacing the electrodes with polycrystalline films or pellets. On the other hand, the high cost of single-crystal electrodes, remains a seriously limiting factor in the fabrication of metal/CdSe solar cells. Using polycrystalline films is an interesting approach, however, and as a result there has been considerable interest in developing new polycrystalline thin film semiconductors, such as Sb$_2$S$_3$ or CdSe. These polycrystalline films can be prepared by many methods, such as electrodeposition, vacuum evaporation, screen printing, spray pyrolysis, and pressure sintering. Among them, chemical deposition deserves special attention because it has been to be an inexpensive, low temperature, and nonpolluting method. Moreover, the quality of the films in terms of the electrical and optical properties can be altered easily by incorporating suitable species in the chemical bath. Thus, sophisticated technologies, such as photolithography diffusion, ion implantation, etc., are not required to create a material with the desired properties. The method is also very suitable for making large area films of any configuration. In previous work, we have introduced new chemical methods for the deposition of CdSe and Sb$_2$S$_3$ thin films and demonstrated that there is significant improvement in their photovoltaic properties when silicotungstic acid is used in the deposition bath. An improved Au/n-Sb$_2$S$_3$ Schottky diode on the n-Sb$_2$S$_3$ film deposited with STA ($n = 1.08, J = 1.5 \times 10^{-8} \text{A/cm}^2$) with a barrier height enhanced up to 0.76 eV and a higher ideality factor ($n = 1.3 \times 10^{-9} \text{A/cm}^2$) for Pt/CdSe. The ideality factor is close to unity

## Results and Discussion

### Structural, electrical, and optical properties

The n-CdSe and n-Sb$_2$S$_3$ films were characterized through resistivity, Hall effect measurements, x-ray diffraction (XRD), neutron activation analysis (NAA), x-ray photoelectron spectroscopy (XPS), and optical absorption measurements as described in our earlier publications.

The resistivity and carrier concentration measurements were carried out by the classical Hall effect technique on CdSe and Sb$_2$S$_3$ films deposited with and without STA and are summarized in Table 1. The measured values of the resistivity, and carrier concentration of electrodes deposited with and without STA have approximately the same resistivity, carrier concentration, and carrier mobility. On the other hand, it may be seen from Fig. 1 and 2 that the optical absorption ($\alpha h\nu$) vs. incident photon energy ($h\nu$) curves change for CdSe and Sb$_2$S$_3$ films deposited with and without STA. An identical ITO-coated glass substrate was used as the reference and the values of the optical absorption coefficient ($\alpha$) were not corrected for the reflectance of the ITO glass surface. The values of the optical bandgap ($E_g$) do not change significantly for films deposited with and without STA. However, for both CdSe and Sb$_2$S$_3$ films, the optical absorption coefficients of electrodes deposited with STA ($\sigma$) are higher than those of films deposited without STA ($\sigma$).

### Solar cell properties

The dark I-V characteristics of the Pt/n-CdSe(STA) and 0.09 cm$^2$ Pt/n-CdSe Schottky diode were measured at room temperature (300 K). Nearly the same characteristics were obtained on structures 0.09 and 0.08 cm$^2$ in area. The ideality factor $n$, barrier height $\Phi_b$, and reverse saturation current density ($J_b$) were used to characterize the properties of the fabricated devices and to compare the effects of STA. The good quality of these Schottky diodes may be seen from Fig. 3. They follow the linear relationship of the ln($J$) vs. $V$ plot over at least four orders of current, and they have very low reverse current densities: $J_b = 1.3 \times 10^{-9} \text{A/cm}^2$ for Pt/CdSe(STA) and $J_b = 3.8 \times 10^{-8} \text{A/cm}^2$ for Pt/CdSe. The ideality factor is close to unity (e.g., 1.04) for the Pt/CdSe(STA) film, whereas a higher value of $n$ (e.g., 1.04) is obtained for the Pt/CdSe.

### Experimental

The Schottky barrier structures were fabricated on low cost chemically deposited polycrystalline n-CdSe and n-Sb$_2$S$_3$ films on ITO coated glass. The films deposited with STA are designated CdSe(STA) and Sb$_2$S$_3$ (STA) and those deposited without STA are designated CdSe and Sb$_2$S$_3$. The film preparation methods have been reported previously.

### Table 1. Resistivity $\rho$, carrier concentration ($n$) and mobility (µ) of the n-CdSe and n-Sb$_2$S$_3$ films deposited with and without STA and annealed at 430°C.

<table>
<thead>
<tr>
<th>Films</th>
<th>Resistivity ($\rho$) (Ω-cm)</th>
<th>Carrier concentration ($n$) (cm$^{-3}$)</th>
<th>Mobility ($\mu$) (cm$^2$/V-s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CdSe(STA)</td>
<td>3.8</td>
<td>$1.3 \times 10^{20}$</td>
<td>182</td>
</tr>
<tr>
<td>Sb$_2$S$_3$(STA)</td>
<td>5.3 $\times 10^{10}$</td>
<td>1.2 $\times 10^{12}$</td>
<td>9.8</td>
</tr>
<tr>
<td>Sb$_2$S$_3$</td>
<td>7.0 $\times 10^{10}$</td>
<td>1.2 $\times 10^{12}$</td>
<td>9.2</td>
</tr>
</tbody>
</table>
Good rectifications are also observed for both curves in the dark. Analogous behavior was obtained with Ni/CdSe, Ni/CdSe(STA), Au/CdSe, and Au/CdSe(STA) diodes. The saturation current density \(J_0\) and the ideality factor deduced from the dark in \(J-V\) characteristics (forward bias) at 300 K for these different junctions are shown in Table II. The results shown in Fig. 3 and Table II indicate a significant decrease in \(n\) and \(J_0\) for junctions fabricated with STA. For comparison, the forward \(J-V\) characteristics of Pt/Sb\(_2\)S\(_3\) and Pt/Sb\(_2\)S\(_3\)(STA) diodes are presented in Fig. 4. Good rectification is observed for both curves in the dark. From these curves, the ideality factor \(n\) was found to be 1.78 for the Pt/Sb\(_2\)S\(_3\) diode and 1.04 for the Pt/Sb\(_2\)S\(_3\)(STA) junction, whereas the saturation-current densities were \(2.1 \times 10^{-7}\) A cm\(^{-2}\) and \(1.5 \times 10^{-9}\) A cm\(^{-2}\) respectively. Similar trends were observed with the Ni/Sb\(_2\)S\(_3\), Ni/Sb\(_2\)S\(_3\)(STA), Pt/Sb\(_2\)S\(_3\), and Pt/Sb\(_2\)S\(_3\)(STA) diodes. The different values of \(J_0\) and \(n\) deduced from the dark in \(J-V\) characteristics (forward bias) at 300 K for these different junctions are shown in Table III. A significant decrease in \(n\) and \(J_0\) occurred for the junctions fabricated with STA. Probably, the formation of a WO\(_3\) interfacial layer, as confirmed by XPS and NAA analysis, plays an important role in the electronic charge-transfer in the device and leads to the improvement in \(n\) and \(J_0\). Figure 5(I) and (II) shows the \(J-V\) characteristics of Pt/CdSe films deposited without STA: barrier height \(h_0 = 0.59\) eV, \(J_0 = 3.8 \times 10^{-9}\) A cm\(^{-2}\), and ideality factor \(n = 1.04\), and (III) for the CdSe films deposited with STA: barrier height \(h_0 = 0.81\) eV, \(J_0 = 1.3 \times 10^{-9}\) A cm\(^{-2}\), and ideality factor \(n = 1.04\).

![Fig. 1. Variation in \((\alpha h)^{1/2}\) vs. \((h v)\) for a typical film on ITO-coated glass substrate: (a) Sb\(_2\)S\(_3\) film prepared with 10\(^{-4}\)M STA and annealed at 300\(^\circ\)C in an N\(_2\) atmosphere for 1 h, (b) same as (a) but without STA.](image)

![Fig. 2. Variation in \((\alpha h)^{1/2}\) vs. \((h v)\) for a typical film on ITO-coated glass substrate: (a) as-deposited CdSe films, (b) same as (a) but annealed at 430\(^\circ\)C in air for 1 h, and (c) same as (b) but the CdSe film is prepared with 10\(^{-4}\)M STA.](image)

![Fig. 3. Dark \(J-V\) characteristics (forward bias) at 300 K for Pt/n-CdSe: (I) for the CdSe films deposited without STA: barrier height \(h_0 = 0.59\) eV, \(J_0 = 3.8 \times 10^{-9}\) A cm\(^{-2}\), and ideality factor \(n = 1.04\), and (III) for the CdSe films deposited with STA: barrier height \(h_0 = 0.81\) eV, \(J_0 = 1.3 \times 10^{-9}\) A cm\(^{-2}\), and ideality factor \(n = 1.04\).](image)

Table II. Ideality factor \(n\) and saturation current density \(J_0\) deduced from \(J-V\) characteristics (forward bias) at 300 K for different metal/CdSe Schottky junctions.

<table>
<thead>
<tr>
<th>Junction</th>
<th>(n)</th>
<th>(J_0) (A/cm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni/CdSe(STA)</td>
<td>2.21</td>
<td>6.2 \times 10^{-9}</td>
</tr>
<tr>
<td>Au/CdSe(STA)</td>
<td>2.04</td>
<td>4.2 \times 10^{-9}</td>
</tr>
<tr>
<td>Au/CdSe(STA)</td>
<td>1.12</td>
<td>1.7 \times 10^{-9}</td>
</tr>
<tr>
<td>Ni/CdSe</td>
<td>2.28</td>
<td>6.4 \times 10^{-9}</td>
</tr>
<tr>
<td>Ni/CdSe(STA)</td>
<td>2.04</td>
<td>4.2 \times 10^{-9}</td>
</tr>
<tr>
<td>Ni/CdSe(STA)</td>
<td>1.12</td>
<td>1.7 \times 10^{-9}</td>
</tr>
<tr>
<td>Ni/CdSe</td>
<td>2.21</td>
<td>6.2 \times 10^{-9}</td>
</tr>
<tr>
<td>Ni/CdSe(STA)</td>
<td>2.04</td>
<td>4.2 \times 10^{-9}</td>
</tr>
<tr>
<td>Ni/CdSe(STA)</td>
<td>1.12</td>
<td>1.7 \times 10^{-9}</td>
</tr>
</tbody>
</table>
Au/Sb$_2$S$_3$(STA) 1.08, 1.50 x 10^{-9}

Junction $n$ (mA/cm$^2$)

Table II. Solar cell parameters deduced from I-V characteristics under AM1 illumination for different metal/CdSe and metal/Sb$_2$S$_3$ junctions.

<table>
<thead>
<tr>
<th>Junction</th>
<th>$J_{sc}$ (mA/cm$^2$)</th>
<th>$V_{oc}$ (V)</th>
<th>FF (%)</th>
<th>$n$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni/CdSe</td>
<td>3.90</td>
<td>0.49</td>
<td>0.42</td>
<td>0.60</td>
</tr>
<tr>
<td>Ni/CdSe(STA)</td>
<td>7.92</td>
<td>0.58</td>
<td>0.63</td>
<td>3.55</td>
</tr>
<tr>
<td>Ni/Sb$_2$S$_3$</td>
<td>5.24</td>
<td>0.44</td>
<td>0.31</td>
<td>0.3</td>
</tr>
<tr>
<td>Ni/Sb$_2$S$_3$(STA)</td>
<td>6.23</td>
<td>0.63</td>
<td>0.54</td>
<td>2.14</td>
</tr>
<tr>
<td>Au/CdSe</td>
<td>4.2</td>
<td>0.61</td>
<td>0.48</td>
<td>1.03</td>
</tr>
<tr>
<td>Au/CdSe(STA)</td>
<td>11.80</td>
<td>0.63</td>
<td>0.68</td>
<td>5.1</td>
</tr>
<tr>
<td>Au/Sb$_2$S$_3$</td>
<td>2.80</td>
<td>0.48</td>
<td>0.32</td>
<td>0.4</td>
</tr>
<tr>
<td>Au/Sb$_2$S$_3$(STA)</td>
<td>7.85</td>
<td>0.68</td>
<td>0.56</td>
<td>3.0</td>
</tr>
<tr>
<td>Pt/CdSe</td>
<td>5.64</td>
<td>0.64</td>
<td>0.81</td>
<td>1.4</td>
</tr>
<tr>
<td>Pt/CdSe(STA)</td>
<td>11.72</td>
<td>0.72</td>
<td>0.70</td>
<td>7.2</td>
</tr>
<tr>
<td>Pt/Sb$_2$S$_3$</td>
<td>3.6</td>
<td>0.52</td>
<td>0.38</td>
<td>0.7</td>
</tr>
<tr>
<td>Pt/Sb$_2$S$_3$(STA)</td>
<td>11.3</td>
<td>0.77</td>
<td>0.63</td>
<td>5.5</td>
</tr>
</tbody>
</table>

Table III. Ideality factor ($n$) and saturation current density ($J_0$) deduced from In-J-V characteristics (forward bias) at 300 K for different metal/Sb$_2$S$_3$ junctions.

<table>
<thead>
<tr>
<th>Junction</th>
<th>$n$</th>
<th>$J_0$ (A/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni/Sb$_2$S$_3$</td>
<td>2.44</td>
<td>4.8 x 10^{-9}</td>
</tr>
<tr>
<td>Ni/Sb$_2$S$_3$(STA)</td>
<td>1.16</td>
<td>5.8 x 10^{-9}</td>
</tr>
<tr>
<td>Au/Sb$_2$S$_3$</td>
<td>2.32</td>
<td>3.2 x 10^{-9}</td>
</tr>
<tr>
<td>Au/Sb$_2$S$_3$(STA)</td>
<td>1.08</td>
<td>1.50 x 10^{-9}</td>
</tr>
</tbody>
</table>

Fig. 4. Dark In J-V characteristics (forward bias) at 300 K for Pt/n-Sb$_2$S$_3$: (I) for the n-Sb$_2$S$_3$ films deposited without STA: barrier height $\phi_B = 0.81$ eV, $J_0 = 1.8 \times 10^{-9}$ A/cm$^2$, and ideality factor ($n$) = 1.06.

Fig. 5. Illuminated I-V characteristics of Pt/n-CdSe Schottky devices: (I) for the CdSe films deposited without STA: $V_{oc} = 0.72$ V, $J_{sc} = 14.2$ mA/cm$^2$, $FF = 70.3\%$, and efficiency ($\eta$) = 7.2% and (II) for CdSe films deposited with STA: $V_{oc} = 0.54$ V, $J_{sc} = 5.04$ mA/cm$^2$, $FF = 51\%$, and efficiency ($\eta$) = 1.4%.

Fig. 6. Illuminated I-V characteristics of Pt/n-Sb$_2$S$_3$ Schottky devices: (I) for the Sb$_2$S$_3$ films deposited without STA: $V_{oc} = 0.77$ V, $J_{sc} = 11.3$ mA/cm$^2$, $FF = 63\%$, and efficiency ($\eta$) = 5.5% and (II) for Sb$_2$S$_3$ films deposited with STA: $V_{oc} = 0.52$ V, $J_{sc} = 3.6$ mA/cm$^2$, $FF = 38\%$, and efficiency ($\eta$) = 0.7%.

Fermi level pinning effect.—From Fig. 9, and Tables V and VI, no significant variation is observed in $V_{oc}$ and $W$ in a range of more than 1 eV for both types of diodes fabricated with the films deposited with and without STA. This may indicate that the Fermi levels are pinned at these interfaces. Further support for this observation may be obtained by determining the barrier heights of these junctions. The C-V measurements (1 MHz) were carried out to determine the $\phi_B$ values. The 1/C$^2$-V plots for the Pt/CdSe, Pt/CdSe(STA), Pt/Sb$_2$S$_3$, and Pt/Sb$_2$S$_3$(STA) devices are shown in Fig. 11 and 12. The junctions formed with the n-CdSe and Sb$_2$S$_3$ films deposited with (STA) (Fig. 11(I) and 12(I))...
This indicates that the Fermi levels are pinned at the metal/CdSe, metal/CdSe(STA), metal/Sb₂S₃, and metal/Sb₂S₃(STA) diodes. Furthermore, the presence of Fermi level pinning on metal/CdSe(STA) and metal/Sb₂S₃(STA), in spite of the improvement in their ϕᵣ or Vᵣ, indicates that the beneficial effects of the STA species in the films observed on metal/CdSe(STA) and metal/Sb₂S₃(STA) do not contribute to the suppression of the Fermi level pinning. It is interesting to note that this behavior is independent of the band structure of the semiconductor. Fermi level pinning is generally attributed to the presence of a high interface density, surface states, or carrier injection due to sufficient band-bending to change the relative carrier density. It is interesting to note that for CdSe (Eᵥ = 1.70 eV) and Sb₂S₃ (Eᵥ = 1.74 eV) deposited without STA the Fermi levels are “pinned” at barrier heights very close to one-third (0.57 eV) of the bandgap from the valence-band edge. These results are similar to those obtained on Si, GaAs, GaP, and other semiconductors. Most covalent semiconductor surfaces having a high peak density, surface states, or defects show Fermi level pinning.

Fig. 7. Variations in Jₛ with the metal work function (W): (○) for metal/n-CdSe(STA), (△) for metal/n-CdSe, (●) for metal/n-Sb₂S₃(STA), and (□) for metal/n-Sb₂S₃.

Fig. 8. Variations in η with the metal work function (W): (○) for metal/n-CdSe(STA), (△) for metal/n-CdSe, (●) for metal/n-Sb₂S₃(STA), and (□) for metal/n-Sb₂S₃.

Fig. 9. Variations in Vᵣ with the metal work function (W): (○) for metal/n-CdSe(STA), (△) for metal/n-CdSe, (●) for metal/n-Sb₂S₃(STA), and (□) for metal/n-Sb₂S₃.

Fig. 10. n-CdSe/n-WO₃ or n-Sb₂S₃/n-WO₃ heterojunction band diagram.

and Fig. 12(I) showed higher intercept voltages (Vᵣ), 0.74 and 0.63 V, giving barrier heights (ϕᵣ) of 0.83 and 0.81 eV, respectively, whereas the diodes fabricated with the n-CdSe and n-Sb₂S₃ films without STA showed a lower Vᵣ, giving ϕᵣ of 0.50 and 0.43 eV, respectively. From the slopes of the curves, the carrier concentrations were determined, and the values are summarized in Table I. Films deposited with STA have the same carrier concentrations as those deposited without STA. These values are consistent with the values determined by Hall measurements. The barrier heights are also in close agreement with those determined from the curves in Fig. 3 and 4. The ϕᵣ values of the Schottky diodes on CdSe, CdSe(STA), Sb₂S₃, and Sb₂S₃(STA) are summarized in Table V and VI, respectively. The ϕᵣ and Vᵣ values of metal/CdSe(STA) are ~200 mV greater than those of metal/CdSe diode. On the other hand, the barrier height of the metal/CdSe or the metal/CdSe(STA) diodes are practically independent of the metal work function (W) in a range of more than 1 eV. The same trend is observed if we compare the barrier heights of metal/Sb₂S₃(STA) to those of metal/Sb₂S₃ (see Table VI). This indicates that the Fermi levels are pinned at the metal/CdSe, metal/CdSe(STA), metal/Sb₂S₃, and metal/Sb₂S₃(STA) diodes. Furthermore, the presence of Fermi level pinning on metal/CdSe(STA) and metal/Sb₂S₃(STA), in spite of the improvement in their ϕᵣ or Vᵣ, indicates that the beneficial effects of the STA species in the films observed on metal/CdSe(STA) and metal/Sb₂S₃(STA) do not contribute to the suppression of the Fermi level pinning. It is interesting to note that this behavior is independent of the band structure of the semiconductor. Fermi level pinning is generally attributed to the presence of a high interface density, surface states or carrier injection due to sufficient band-bending to change the relative carrier density. It is interesting to note that for CdSe (Eᵥ = 1.70 eV) and Sb₂S₃ (Eᵥ = 1.74 eV) deposited without STA the Fermi levels are “pinned” at barrier heights very close to one-third (0.57 eV) of the bandgap from the valence-band edge. These results are similar to those obtained on Si, GaAs, GaP, and other semiconductors. Most covalent semiconductor surfaces having a high peak density, surface states, or defects show Fermi level pinning.
level pinning near one-third of the bandgap from the valence-band edge. For CdSe and Sb$_2$S$_3$ films deposited with STA that have the same bandgap as the films deposited without STA, the Fermi level is pinned at a point slightly below the center of the forbidden gap (e.g., 0.78 eV) of these semiconductors. Accordingly, these Fermi levels are pinned at a position different from that of films deposited without STA. This position of the "pinned" Fermi levels in the case of the films deposited with STA agrees well with that obtained by Pugh 16 from the theoretical calculations for <111> diamond, and it is observed that the Fermi level of diamond is pinned at a point slightly below the center of the forbidden gap. Our results on the films deposited with STA indicate evidence of the presence of a narrow band of surface or interface states slightly below the center of the forbidden gap of these two semiconductors.

### Conclusion

The solar cell properties of Schottky diodes using the metals Pt, Au, and Ni on CdSe or Sb$_2$S$_3$ thin films chemically deposited with and without STA are reported. Based on the results obtained here, it may be concluded that:

1. A significant improvement in the Schottky barrier solar cell parameters was obtained with the CdSe or Sb$_2$S$_3$ films deposited with STA.

2. The improvement in solar cell properties was attributed to the presence of WO$_3$ in the films deposited with STA.

3. The absorption coefficient is improved due to the presence of WO$_3$ in the films.

4. The Fermi levels of the junctions fabricated with the CdSe or Sb$_2$S$_3$ films deposited with or without STA are pinned. For Schottky diodes fabricated with the CdSe or Sb$_2$S$_3$ films deposited without STA, the Fermi levels are pinned at one-third of the bandgap from the valence-band edge. For junctions fabricated with CdSe or Sb$_2$S$_3$ deposited with STA, the Fermi levels are pinned at a point slightly below the center of the forbidden gap.

### Acknowledgments

The authors wish to thank Natural Science and Engineering Research Council of Canada and le Ministère des Ressources Naturelles du Québec for their financial support.

Manuscript submitted Feb. 7, 1994; revised manuscript received May 17, 1994.

École Polytechnique de Montréal assisted in meeting the publication costs of this article.

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Electroluminescence and Photoluminescence of Cerium-Activated Alkaline Earth Thiogallate Thin Films and Devices

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ABSTRACT

Thin films of cerium-activated alkaline earth thiogallate were investigated for the fabrication of blue-emitting thin-film electroluminescent (TFEL) devices. The films were prepared by RF sputtering from targets with composition: $M_{1-x}$Ga$_2$S$_4$Ce$_x$, where $M$ = Ba, Ca, Sr, and 0.01 $\leq$ $x$ $\leq$ 0.1. Photoluminescent (PL) emission spectra showed matching peak wavelengths to those obtained from electroluminescent (EL) emission for each alkaline earth thiogallate film. The optimum cerium concentration for EL emission intensity for strontium and calcium thiogallate films was determined to be $x$ = 0.04 and 0.06, respectively. The EL brightness measured for the calcium thiogallate devices was almost twice that measured for the strontium thiogallate devices. This brightness variation, however, is due mainly to the difference in the lumen equivalent of the emission intensity. The cerium concentration dependence of the PL emission spectra of the thiogallate films is substantially decreased compared with the respective powder material suggesting inhomogeneous cerium incorporation in the films.

The CIE chromaticity coordinates of the blue TFEL emitting for the cerium-doped calcium thiogallate phosphor are sufficient to produce a wide color gamut and a true white color when combined with EL red and green phosphors in a CRT blue phosphor are sufficient to produce a wide color gamut and a true white color when combined with EL red and green phosphors in a CRT blue phosphor. Peters and Baglio have reported cathodoluminescent (CL) spectra, CL efficiencies, and relative photoluminescence intensities for $M^2$Ga$_2$S$_4$Ce$_x$Na ($M$ = Ca, Sr, and Ba) powders having a Ce$^{3+}$ concentration of 2 atomic percent (a/o). They did not, however, report on the cerium concentration dependence of the luminescence properties for these phosphors.

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