CHAPTER - 6

CONCLUSIONS

AND

FURTHER SCOPE OF THE WORK
CONCLUSIONS

Looking at the introduction given in Chapter 1, it was heard that liquid junction solar cells could prove as an alternative for the solid junction solar cells because of some of their attractive features. Therefore the present investigation was centered around the growth of MoSe₂ crystals and their subsequent characterization and further applications as photodelectrodes in liquid junction photoelectrochemical solar cells. From the characterization of MoSe₂ crystals grown in present investigations, following things can be inferred.

1) MoSe₂ crystals grown using the vapour transport technique possesses hexagonal structure.

2) MoSe₂ crystals are observed to possess a high degree of purity (as measured by the EDAX technique reported in Chapter 2) when they are grown by the direct vapor transport technique wherein no extra transporting agent is being used.

3) MoSe₂ crystals grown in present investigations possesses both, p- and n-type conductivities. This can be attributed to the presence of excess or deficiency of selenium during the growth process.

4) The electrical resistivity of MoSe₂ crystals along the surface directions (a-axis) is found to be of the order of few ohms.

5) The electrical resistivity of the MoSe₂ crystals along the thickness direction where the layers of Se-Mo-Se have been coupled via weak Van der Waal forces (along c-axis) if found to be of the order of few K ohms.

6) From points 6 and 7 it is quite apparent that MoSe₂ crystals possesses different resistivities along different directions. As discussed in Chapter 1, MoSe₂ is a material belonging to group VI Transition Metal Dichalcogenides, which has layered structures. Thus a strong chemical bonding along the a-axis (surface direction) leads to low resistivity whereas a weak Van der Waal type bonding
between the layers along the c-axis gives rise to a high resistivity values. In present investigations, the anisotropy factor is found to be of the order of $10^3$.

7) The value of energy gap of MoSe$_2$ crystals obtained from the study of the variation of its resistivity with temperature in high temperature region was found to be $1.37\text{eV}$, which is close to the standard value.

8) From the optical characterization it could be confirmed that MoSe$_2$ material grown in present case possesses both, the direct and indirect transitions. The energy gap corresponding to the indirect transition is as usual found to be lower than that for the direct transitions as seen from Chapter 3.

9) The application of magnetic field changes the conductivity property of MoSe$_2$ crystals. Using this change, various parameters of MoSe$_2$ crystals like the Hall coefficient, mobility and the carrier concentration were estimated and found to be $159.8 \text{ cm}^3/\text{Coul}$, $399.6 \text{ cm}^2/\text{Volt.Sec}$ and $3.91\times10^{16} \text{ cm}^{-3}$ respectively.

10) From the thermopower measurements, it was seen that the crystals under investigations were n-type in nature.

From all these inferences it is clear that MoSe$_2$ crystals can be used for the optoelectronic devices provided the a-axis should be brought in contact with the electrolyte. From the energy band scheme of MoSe$_2$ materials shown in Chapter 1, it can be concluded that MoSe$_2$ material can prove to be stable against corrosion and decompositions in presence of the electrolyte.

n-type MoSe$_2$ crystals have been used as photoanodes in MoSe$_2$ / I$_2$ / I$^-$ / Pt PEC solar cells. These cells have been characterized for their photoconversion behaviour. Following conclusions can be drawn from the study of the photoconversion behaviour and the stability of MoSe$_2$ PEC solar cells.
1) The efficiency of MoSe$_2$ PEC solar cells reported in present thesis have been found to be low. Various reasons have been attributed for this low photoconversion efficiency. It is to be noted here that MoSe$_2$ crystals have been used as photoanodes in PEC solar cells under as grown conditions (non chemical or thermal treatment or passivation technique has been applied prior to the fabrication of photoanodes). This is also one of the reasons for low photoconversion efficiency.

2) The fill factor of MoSe$_2$ PEC solar cells is found to be less than 0.5. This is again a reflection of poor photoconversion behaviour of such cells.

3) From the study of the variation of short circuit current and the open circuit voltage with the intensity of incident illumination, it has been concluded that the electrochemical kinetics starts affecting the photoconversion characteristics of MoSe$_2$ PEC solar cells adversely above $I_L = 60$ mW/cm$^2$. Hence it must be kept in mind that these cells can operate linearly and faithfully in a range of intensities of incident illumination from 10 mW/cm$^2$ to 60 mW/cm$^2$ above which the efficiency decreases which is never advisable.

4) As mentioned earlier, the photoconversion characteristics which have been reported in Chapter 4 were accomplished with MoSe$_2$ photoanodes without giving any treatment (prior to or after fabrication of photoanode), efforts have been made to investigate the effect of temperatures on the overall photoconversion behaviour of MoSe$_2$ PEC solar cells. It was interestingly observed that the photoconversion characteristics of these cells improve with the thermal treatment as observed from the improvement in the values of various parameters reported in Chapter 4. In addition to this it was seen that the series resistance of the cell decreases with thermal treatment, which is one of the prime reason for the improvement in the photoconversion characteristics of MoSe$_2$ PEC solar cells.
5) From the study of monochromatic photoresponse the following general conclusion can be drawn:

The photoconversion characteristics improve as the wavelength of the incident radiation moves towards red / infrared region. This is a very well expected behaviour because the maximum absorption of the incident photons reaches to the optimum value of energy lying in the infrared region (it is an inference from the value of band gap energy of MoSe\textsubscript{2}).

6) From the potentiodynamic measurements, the corrosion rate of MoSe\textsubscript{2} PEC solar cell was evaluated and found to be of the order of $10^4$ MPY. This directly indicate that the PEC cells under investigation must be highly stable against the corrosion / decomposition in presence of the iodine electrolyte.

7) From the value of polarization resistance, it can be inferred that MoSe\textsubscript{2} material offers a high resistance for the corrosion or decompositions.

From the above two conclusions it is quite apparent that the PEC solar cells under investigations possesses high stability.

8) The efficiency of the MoSe\textsubscript{2} PEC solar cells was investigated regularly at an interval of time for quite a long period of time and following things were observed.

a) The efficiency remains almost constant for 300 hours

b) The fill factor remains almost constant for 300 hours.

c) The degradation of photoelectrode, which was continuously left in electrolyte, was a little faster than that for the electrode, which was dipped only while taking the measurements.

The high stability of MoSe\textsubscript{2} PEC solar cells has been explained in Chapter 5 on the basis of d-d transitions of photo generated carriers taking place without disturbing the normal covalent bonding between Mo and Se atoms.
FURTHER SCOPE

As discussed above, MoSe$_2$ crystals have been used as photosensitive electrode in PEC solar cells prior to giving any treatment. It will be always interesting to see the changes in the photoconversion characteristics of such cells after giving thermal and chemical treatments. From the little coverage of the thermal treatment on MoSe$_2$ PEC solar cells reported in Chapter 5, it can be predicted that the rigorous chemical and thermal treatment (individually or / and a combination of two) may lead to large improvement in the photoconversion characteristics. It will always be interesting to investigate the stability of such cells after the above treatments.

Finally, a lot of materials have come up recently which show the ionic conduction mechanism and hence, can be used as solid electrolytes. Hence it will be a challenging task to find out a suitable material, which can be used as a solid electrolyte in PEC solar cells. If this is achieved, many important drawbacks of PEC solar cells can be overcome.
REFERENCES:


[14] R. Parson,

[15] P. Delahay,

[16] C.A. Barlow,


[18] J.F. Dewald,

[19] M. Green,

[20] P.J. Holmes,

[21] H. Gerischer,

[22] R. Memming,

[23] R. Memming,

[24] Y.A. Myamlin and Y.U.V. Pleskov,

[25] A.K. Vijn,
Electrochemistry of metals and semiconductors (Marcel Dekker, New York), (1973).

[26] P.I. Boddy,
[27] H. Gerischer, 

[28] H. Gerischer, 

[29] D. Cahen, B. Vainas and J. M. Vandenberg, 

[30] W. W. Anderson and Y. G. Chai, 

[31] A. B. Ellis, S. W. Kaiser and M. S. Wrighton, 

[32] A. B. Ellis, S. W. Kaiser and M. S. Wrighton, 

[33] A. B. Ellis, S. W. Kaiser and M. S. Wrighton, 

[34] A. Aruchamy, A. Venkatnathnam, M. Subrahmanyam, G. A. Subba Rao, and G. Aravamudan, 

[35] K. Nakatani, M. Matsud and H. Tsubomura, 

[36] A. Heller, K. C. Chang and B. Miller, 

[37] A. Heller, K. C. Chang and B. Miller, 

[38] B. Miller and A. Heller, 


[40] S. Chandra, R. K. Pandey and R. C. Agarwal, 


[69] A. Heller, 
In Photoeffects at Semiconductor Electrolyte Interface, ed. A. J. Nozik, 
ACS Symposium Series (American Chemical Society, New York)  

[70] R. Noufi and D. Tench, 

[71] W. H. Laflere, F. Cardon and W. P. Gomes, 

[72] P. A. Kohl and A. J. Bard, 

[73] L. Hollan, J. C. Tanchart and R. Memming, 

[74] F. W. Ostermayer and P. A. Kohl, 

[75] F. R. Fan, H. S. White, B. Wheeler and A. J. Bard, 

[76] A. B. Ellis, J. M. Bollis and M. S. Wrighton, 

[77] S. Gourg and D. Elliot, 

[78] P. A. Kohl and A. J. Bard, 

[79] S. Chandra and N. Khare, 

[80] Y. Kamprakash, S. Basu and D. N. Bose, 
In proceedings of the National Solar Energy Conven., India, (1979) 392.

[81] M. J. Madou, F. Cardon and W. P. Gomes, 
In Proceedings of the Photovoltaic Solar Energy Conference, 
Luxemberg, (1977b).

[82] A. Heller and R. G. Vadimsky, 
[83] M. Halmann and B. Aurian-Blajeni,  
In proceedings of Photovoltaic Solar Energy Conference, Berlin (West)  
April 23–26, (1979).

[84] D.C. Book Binder, J.A. Bruce, R.N. Dominey, N.S. Lewis and  
M.S. Wrighton,  

[85] T.S. Jayadevaiah,  

[86] K.D. Legg, A.B. Ellis, J.M. Bolts and M.S. Wrighton,  

[87] J.M. Bolts, A.B. Bocarsly, M.C. Palazzotto, E.G. Walton, N.S. Lewis and  
M.S. Wrighton,  

[88] M.S. Wrighton, A.B. Bocarsly, J.M. Bolts, A.B. Ellis and K.D. Legg,  
In Semiconductor Liquid Junction Solar Cells, ed. A. Heller,  

[89] T. Skotheim, L. Lundstrom and J. Preja,  

[90] H. Tributsch,  

[91] H. Tributsch,  

[92] J. Gobrecht, H. Tributsch and H. Gerischer,  

[93] G. Kline, K. Kam, D. Canfield and B.A. Parkinson  

[94] M.K. Agarwal, V.P. Patil, and P.D. Patil,  

[95] W. Kautek and H. Gerischer,  

[96] C.P. Kubiak, L.F. Schneemeyer and M.S. Wrighton,  


[125] J. Gobrecht, H. Tributsch and H. Gerischer, 

[126] H. Tributsch, 

[127] C. Clemen, X. I. Saldana, P. Munz and E. Bucher, 

[128] W. Kautek, H. Gerischer and H. Tributsch, 

[129] L. F. Schneemeyer and M. S. Wrighton, 

[130] F. J. S. Menezes, Disalvo and B. Miller, 

[131] P. G. P. Ang and A. F. Sammells, 

[132] T. Kawai, H. Tributsch and T. Sakata, 

[133] G. Nagasubramaniam and H. S. White, 

[134] H. J. Lewerenz, A. Heller and F. J. Disalvo, 

[135] W. Kautek, J. Gobrecht and H. Gerischer, 

[136] W. Kautek and H. Gerischer, 

[137] W. Kautek, H. Gerischer and H. Tributsch, 


[139] B. A. Parkinson, T. E. Furtek, D. Canfirld, K. K. Kam and H. S. White, 
[140] L.F.Schneemeyer and M.S.Wrighton, 

[141] C.P.Kubiak, L.F.Schneemeyer and M.S.Wrighton, 

[142] M.S.Kazacos, J.F.McCann and D.Haneman, 

[143] W.Kautek and F.Willing, 

[144] A.Heller, B.Miller and F.A.Thiel, 

[145] D.Canfield and B.A.Parkinson, 

[146] S.Menezes, L.F.Schneemeyer and H.J.Lerenz, 

[147] H.Tributsch, T.Sakata and T.Kawai, 

[148] G.Djemal, N.Mular, U.Lachish and D.Cahen, 

[149] M.L.Phillips and M.T.Spitler, 

[150] L.Fornarini, F.Stripe, B.Scrosati and G.Razzini, 

[151] R.Audas and J.C.Irwin, 

[152] K.W.Mitchell and L.B.Fabick, 
(New York, USA, IEE, 1981) 130.

[153] H.S.White, F.R.F.Fan and A.J.Bard, 

[154] P.G.P.Ang and A.F.Sammells, 


[170] S.M. Ahmed, 

[171] G. Nagasubramaniam, B.L. Wheeler and A.J. Bard, 

[172] A. Aruchamy, G. Arvamudan and G.V. Subbarao, 

[173] G. Nagasubramaniam, B.L. Wheeler, G.A. Hope and A.J. Bard, 

[174] L. Fornarini, F. Stripe and B. Scrosati, 

[175] H.J. Lewerenz, H. Gerischer and M. Lubke, 

[176] S. Prybyla, W. S. Struve and B. A. Parkinson, 

[177] L.P. Bicelli and G. Razzini, 

[178] L.P. Bicelli and G. Razzini, 

[179] E. Kamieniecki, 

[180] L.P. Bicelli and G. Razzini, 

[181] M. Szkarczyk and J.O'm. Bockris, 

[182] S. Chandra, D.P. Singh, P.C. Srivastava and S.N. Sahu, 

[183] Livia Stoicovicia and R.M. Candea, 

[184] H.J. Lewerenz, H. Tribusch and M. Spiesser, 


[200] M.K.Agawal, V.V.Rao and V.M.Pathak, 

[201] M.K.Agawal and G.H.Yousefi, 

[202] M.K.Agawal and V.V.Rao, 

[203] M.K.Agawal and V.V.Rao, 


[205] M.A.Green, 

[206] A.G.Sarkissyan, 

[207] W.Sienicki, T.Hryniewicz, 

[208] H.Naruke, N.Wakatsuki and Y.Hoshi, Y.Sasaki, 

[209] M.A.Green, K.Emery, K.Bucher, D.L.King and S.Igar, 

[210] M.A.Green, K.Emery, K.Bucher, D.L.King and S.Igar, 

[211] M.A.Green, K.Emery, K.Bucher, D.L.King and S.Igar, 


[213] H.E. Buckley, 

[214] A.VanHook, 
[215] J.G. Burke,

[216] D. Elwell and H. Scheel,

[217] A. Holden and P. Singer,

[218] A. Holden and P. Morrison,

[219] P. Kratochvil,

[220] I. Tarjan and M. Matrai,
Laboratory Manual on Crystal Growth (Budapest, Akademiai Kiado), (1972).

[221] K. Th. Wilke,
Kristallzuchtrung (Berlin, VEB Deutscher Verlag der Wissenschaften), (1973).

[222] B. R. Pamplin,
Crystal Growth (Oxford, Pergamon), (1980).

[223] R. A. Laudise,

[224] J. J. Gilman,

[225] P. Hartman,
Crystal Growth: An Introduction (Amsterdam, North Holland), (1973).

[226] A. A. Chernov,

[227] M. M. Faktor and I. Garrett,
[228] H.K.Henisch,

[229] J.C.Brice,
The Growth of Crystals from Liquids. (Amsterdam, North Holland),
(1973).

[230] F.Rosenberger,

[231] J.C.Wildervanck,

[232] (a) E.Wendehorst,
(b) L.C.Towel, V.Oberbeck and B.E.Brown,

[233] M.S.Silverman,

[234] A.A.Al-Hilli and B.L.Evans,

[235] L.H.Brixner,

[236] H.Schafer, F.Weihmeier and M.Trenkel,

[237] J.A.Wilson and A.D.Yoffe,

[238] R.Nitsche,

[239] R.Nitsche, H.U.Boelsterli and M.Lichtensteiger,

[240] H.Schafer,

[241] R.Nitsche,
"Crystal Growth" Editor H.S. Peiser Pergaman Oxford.,


[257] A.J. Grant, T.M. Griffiths and A.D. Yoffe, 

[258] F. Levy, Ph. Schmid and H. Berger, 
Phil. Mag., 34 (1976) 1129.

[259] R. Fivaz and E. Mooser, 

[260] M.K. Agarwal and P.A. Wani, 

[261] E. Rovolinsky and D. Beemtsen, 

[262] M.K. Agarwal, P.D. Patel and O. Vijanan, 

[263] S.H.E. Mahalawy and B.L. Evans, 

[264] L.H. Brixner, 

[265] B. Davey and B.L. Evans, 

[266] Peraldo Bicelli, 

[267] Gurevich and Pleskov, 

[268] S. Chandra, 

[269] P. Allen and A. Hickling, 

[270] H. Tributsch, 

[271] W. Kautek and F. Willing, 
[272] D. Canfield and B. A. Parkinson,

[273] L. Fomarini, F. Stripe and B. Scrosati,

[274] G. Kline, K. K. Kam and R. Ziegler,

[275] G. Razzini, L. P. Bicelli, C. Pini and B. Scrosati,

[276] M. L. Phillips and M. T. Spitler,

[277] M. A. Butler and D. S. Gin ey,

[278] L. P. Bicelli, P. Pederferri and G. Razzini,

[279] T. E. Frautak, D. Canceled and B. A. Parkinson,

[280] H. Gerischer,
In "Photoeffects at semiconductor-electrolyte interface " Ed. A. J. Nozik,

[281] M. A. Butler,

[282] K. Rajeshwar, P. Singh and R. Thapar,

[283] W. W. Gartner,

[284] V. M. Pathak,
Ph.D. Thesis (physics), Sardar Patel University,

[285] P. J. Boddy and W. H. Brattain,

[286] H. Gerischer,
[287] R.H. Wilson,

[288] S.N. Frank and A.J. Bard,

[289] H. Reiss,

[290] B.A. Parkinson, A. Heller and B. Miller,

[291] D. Laser,

[292] J.N. Chazalviel,

[293] R.H. Wilson,

[294] J. Reichman,

[295] M.A. Butler and D.S. Ginley,

[296] J.N. Chazalviel,

[297] J.N. Chazalviel,

[298] K. Rajeshwar,

[299] S. Chandra,
Photoelectrochemical Solar Cells.

[300] M.B. Prince,

[301] J.J. Wysocki,
[302] M.Wolf and H.Rauschenbach,  

[303] B.A.Bhaskare Rao and Nath,  

[304] B.A.Bhaskare Rao and Nath,  

[305] S.Bobbio and F.P.Califano,  

[306] M.A.Green,  

[307] R.J.Handy,  

[308] H.J.Hovel,  

[309] N.G.Wyeth,  

[310] C.Wagner and W.Traud,  

[311] H.Gerischer and W.Mindt,  

[312] H.Gerischer and F.Beck,  

[313] S.M.Ryvkin,  

[314] R.H.Bube,  
"Photoconductivity of Solids.", (1960).

[315] S.M.Ryvkin,  
[316] R.H. Bute,  

[317] L.L. Shreir,  

[318] V.H. Ailor,  

[319] M. Stern and A.L. Geary,  

[320] N. Stern,  
Corrosion, 14 (1958) 440.

[321] J.O'M. Bockis and R.N. Reddy,  

[322] R. Vlick Evans,  

[323] H. Gerischer,  

[324] S. Chandra,  

[325] Yu Ya Gurevich and Yu V. Pleskov,  

[326] H. Gerischer,  

[327] H. Gerischer,  

[328] S. Roy Morrison,  
[329] S.Chandra and R.K.Pandey,

[330] S.Sampath and R.Narayan,

[331] S.Chandra and R.K.Pandey,

[332] D.R.Turner and J.Pankove,

[333] V.M.Pathak,

[334] H.Tributsch,
Structure of Bonding, 49 (1982) 127.
PUBLICATIONS

   Ionic Conducting Materials : Theory and Applications
   Editors A.R.Kulkarni and P.Gopalan,

2. "Improved Photoconversion From MoSe$_2$ Based PEC Solar Cells."
Paper Presented at Conferences/Seminars/Symposiums

1. **Title:** Use of MoSe$_2$ crystals as photoanodes in PEC solar cells.
   **Conference:** 15$^{th}$ Gujarat Science Congress
   **Date/Venue:** 12$^{th}$ & 13$^{th}$ Feb. 2000 at M.S. University, Vadodara.

2. **Title:** Photovoltaic Behaviour of n-MoSe$_2$ / I$_2$ / I$^-$ Interface.
   **Date/Venue:** 3$^{rd}$ & 5$^{th}$ March 2000 at I.I.T. Powai, Bombay-400076.

3. **Title:** Corrosion Measurements of MoSe$_2$ Based PEC Solar Cells.
   **Seminar:** One day seminar on condensed matter physics.
   **Date/Venue:** 5$^{th}$ March 2000 at Dept. of Physics, S.P. University, Vallabhb Vdyanagar.

4. **Title:** Preparation & Electrical Characterization of CdSe Thin Films.
   **Seminar:** One day seminar on condensed matter physics.
   **Date/Venue:** 5$^{th}$ March 2000 at Dept. of Physics, S.P. University, Vallabhb Vdyanagar.

5. **Title:** Growth of MoSe$_2$ Crystals using Vapour Transport Technique.
   **Symposium:** Fundamentals of crystal growth.
   **Date/Venue:** 6$^{th}$ & 7$^{th}$ Nov. 2000 at Anna University, Chennai-600 025.

6. **Title:** Preparation and characterization of CdSe thin films.
   **Conference:** National Conference on Materials and Semiconductor Technologies in Electronic Research.
   **Date/Venue:** 8$^{th}$ to 10$^{th}$ Nov. 2000, G.B. Pant University of Agriculture & Technology, Pantnagar-263145.

7. **Title:** Growth and low temperature electrical characterization of MoSe$_2$ crystal.
   **Seminar:** One day seminar on condensed matter physics-2001.
   **Date/Venue:** 17$^{th}$ March, 2001. Department of Physics, Sardar Patel University, Vallabhb Vdyanagar-388120. Gujarat.

8. **Title:** Growth and Electrical Characterization of MoSe$_2$ Crystals.
   **Conference:** National Conference on Crystal Growth and Characterization.
   **Date/Venue:** 22-23$^{rd}$ March, 2001. S.T. Hindu College, Nagercoil-629002. TamilNadu.
9. Title: Corrosion Investigations on MoSe$_2$/ I$_2$/ I $^-$/Pt PEC solar cells.
   Conference: Tenth National Convention of Electrochemists (NCE-10)
   Date/Venue: 26-27$^{th}$ April, 2001. Central Electrochemical Research
   Institute, Karaikudi, TamilNadu

10. Title: Growth chemical and structural characterization of MoSe$_2$ Crystal.
    Seminar: XXXI National Seminar on Crystallography.
    Date/Venue: 19-22 June, 2001. Multi-Purpose Hall, BARC Training School
             Hostel Anushakti Nagar, Mumbai-400094.

11. Title: Preparation and Electrical Characterization of CdSe Thin Films.
    Seminar: XXXI National Seminar on Crystallography.
    Date/Venue: 19-22 June, 2001. Multi-Purpose Hall, BARC Training School
             Hostel Anushakti Nagar, Mumbai-400094.

12. Title: Investigations on Corrosion Behaviour of MoSe$_2$ Based solar cells
    Conference: First Asian-Pacific Conference and 6$^{th}$ National Convention.

13. Title: Characterization of MoSe$_2$ Based PEC Cells.
    Conference: 5$^{th}$ NCSSI
    Date/Venue: 15-17 Feb.2002, Department of Physics, Nagpur University

14. Title: Growth, Characterization and photovoltaic behaviour of MoSe$_2$ Based
    solar Cells.
    Conference: National Seminar on Physics of Materials for Electronic and
    Optoelectronic Devices.
    Date/Venue: 25-27 Feb.2002, Department of Physics, J.N.Vayas
             University, Jodhpur.

15. Title: On the low temperature resistivity of thermally deposited CdSe
    thin films.
    Conference: National Seminar on Physics of Materials for Electronic and
    Optoelectronic Devices.
    Date/Venue: 25-27 Feb.2002, Department of Physics,
             J.N.Vayas University, Jodhpur.