

Transport Mechanism in $\text{TiO}_2/\text{In}(\text{OH})_x\text{S}_y/\text{Pb}(\text{OH})_x\text{S}_y/\text{PEDOT:PSS}$ eta Solar Cell

Robinson J. Musembi, Bernard O. Aduda, Julius M. Mwabora, Marin Rusu, Konstantinos Fostiropoulos, and Martha Ch. Lux-Steiner

1 Department of Physics, School of Physical Sciences, University of Nairobi, P.O. Box 30197-00100 Nairobi Kenya

2 Helmholtz – Zentrum Berlin für Materialien und Energie, Lise Meitner Campus, Glienicker Strasse 100, 14109, Berlin Germany

Abstract

Transport mechanism studies in $\text{TiO}_2/\text{In}(\text{OH})_x\text{S}_y/\text{Pb}(\text{OH})_x\text{S}_y/\text{PEDOT:PSS}$ eta solar cell have been carried out. The characterizations have been performed both in the dark and under varying illumination intensity for temperature range 200 K – 320 K. The recombination process of the eta solar cell in the dark has been found to be tunneling enhanced, while under illumination it is thermally activated and takes place through exponentially distributed energy recombination levels. The illumination intensity and temperature have also been found to have a strong influence on the device conversion efficiency, with the highest efficiency being realized at 200 K.

1. Introduction

The eta solar cell concept is an emerging concept proposed a few years ago based on the dye sensitized solar cell concept (nanostructured configuration, separation of light absorption from charge transport, and majority carrier type of device) and classical solar cells concept (all solid state, use of inorganic materials) [1, 2, 3]. Dye sensitized solar cell is a majority carrier type of device made up of mainly nanoporous TiO_2 thin film which is covered with dye monolayer and then a liquid electrolyte is applied, the front electrode is provided by the $\text{SnO}_2:\text{F}$ glass substrate while the counter electrode is made from platinum coated glass [4]. On the other hand, the eta solar cell instead of having a monolayer of dye molecule, an extremely thin absorber (eta) material is sandwiched between two wide band gap n- and p- type materials. The eta solar cell is thus a combination of dye sensitized and classical solar cell concepts [5].

A number of devices based on eta concept have been reported with mainly the extremely thin absorber material of choice being CdTe [6], a-Si [7], CuInS_2 [8], and $\text{PbS}/\text{Pb}(\text{OH})_x\text{S}_y$ [9, 10]. Nonetheless, the knowledge about recombination mechanism in eta solar cell is still limited. In this article, we report on transport mechanism characterization of an highly structured

TiO₂/In(OH)_xS_y/Pb(OH)_xS_y/PEDOT:PSS/Au by analyzing temperature dependence of J-V curves in the dark and under illumination.

2. Experimental method

The solar cells based on Pb(OH)_xS_y eta material were fabricated by the following method: the substrate used was a 15 Ω/□ sheet resistance SnO₂:F glass from Forschungszentrum Jülich. The substrate window layer used for our solar cell was 2 μm thick TiO₂ thin films deposited by sol-gel technique at SgLux GmbH. The other thin film layers coated were 80 nm thick indium hydroxyl sulphide, In(OH)_xS_y, and approximately 10 nm thick lead hydroxyl sulphide, Pb(OH)_xS_y, successively by chemical bath deposition method using the following precursors: an aqueous solution containing 0.025 M InCl₃, 0.1 M thioacetamide, and 0.005 M HCl was deposited at 70 °C, and the procedure was repeated three times by preparing fresh chemical bath after every 30 minutes, following a similar procedure as described elsewhere [5, 9, 10]. Likewise, Pb(OH)_xS_y was deposited from an aqueous solution containing 0.05 M Pb(CH₃OOH)₂, 0.2 M NaOH, 0.05 M triethanolamine, and 0.05 M thiourea at 40 °C for 10 minutes. The last thin film layer to be deposited was an electrically conducting polymer material poly(3,4- ethylenedioxythiophene) (PEDOT) doped with water soluble polyelectrolyte known as polystyrene sulfonate acid (PSS), was deposited undiluted by spin coating technique. The solar cell was completed by gold back contacts deposited using a specially made mask which gave solar cells of 0.126 cm² areas [5, 9, 10].

The temperature dependent current voltage ($JV - T$) was performed in an evacuated nitrogen cooled cryostat using Keithley 2400 series current voltage source meter. The light source for the solar simulator was a halogen lamp (General Electric™, 120 V, 300 W, model L268) calibrated to 100 mW/cm² = 1 sun at AM 1.5. The following procedure was followed in performing the experiment: the temperature was first lowered to T = 200 K, and then current voltage measurements were taken beginning with measurements in the dark, followed by 12 successive measurements under illumination. The light intensity was decreased from 100 mW/cm² to 0.05 mW/cm² by use of neutral density filters. The same procedure was applied for each temperature measurement up to 320 K, the temperature being consecutively changed in steps of 10 K.

3. Transport mechanism theory

The one diode model developed for polycrystalline heterojunction thin film solar cell was used for describing and analyzing the $JV - T$ curves of the eta solar cell in the dark and under illumination [11, 12]. The forward current density J of the heterojunction is described by

$$J = J_o \exp\left(\frac{qV}{AkT}\right) = J_{oo} \exp\left(\frac{-E_a}{AkT}\right) \exp\left(\frac{qV}{AkT}\right) \quad 1$$

where A , J_o and kT/q are the ideality factor, saturation current density of the diode and the thermal voltage, respectively. The term J_{oo} is the temperature dependent prefactor, while E_a is the activation energy of the recombination. Equation 1 can be rearranged to give approximation of open circuit voltage as

$$V_{oc} \approx \frac{AkT}{q} \ln\left(\frac{J_{sc}}{J_o}\right) = \frac{E_a}{q} - \frac{AkT}{q} \ln\left(\frac{J_{oo}}{J_{sc}}\right) \quad 2$$

where J_{sc} is the short circuit current density. In equation 2, if we assume A , J_{sc} , and J_{oo} are independent of T , a plot of V_{oc} as a function of T should yield a straight line and the extrapolation to $T = 0$ K gives the activation energy E_a . However when tunneling process is significant, equation 2 can be reorganized to give

$$A \ln J_o = -\frac{E_a}{kT} + A \ln J_{oo} \quad 3$$

A plot of the corrected saturation current density $A \ln J_o$ as a function of the inverse temperature $1/T$, will yield a straight line with a slope giving us a precise value of activation energy E_a . The value of activation energy can guide us in deducing the type of recombination process taking place in a solar cell device: when $E_a = E_g$ (where E_g is the band gap energy) will indicate that recombination is taking place in the bulk of the materials absorber, or interface recombination is dominant when $E_a = E_g$.

4. Results and discussion

The current transport mechanism in $\text{TiO}_2/\text{In}(\text{OH})_x\text{S}_y/\text{Pb}(\text{OH})_x\text{S}_y/\text{PEDOT:PSS}$ eta solar cell characterizations were performed for a cell which showed under AM 1.5 conditions the following parameters: $V_{oc} = 0.249 \text{ V}$, $J_{sc} = 9.24 \text{ mA/cm}^2$, a fill factor of 34% and conversion efficiency of 0.78%.

Figure 1 shows dark $JV - T$ curves for $\text{TiO}_2/\text{In}(\text{OH})_x\text{S}_y/\text{Pb}(\text{OH})_x\text{S}_y/\text{PEDOT:PSS}$ eta solar cell measured at different temperatures together with the J_{sc} as a function of V_{oc} plots. The curves plotted in figure 1 were generated by fitting dark and illuminated $JV - T$ curves using models described in section 3.

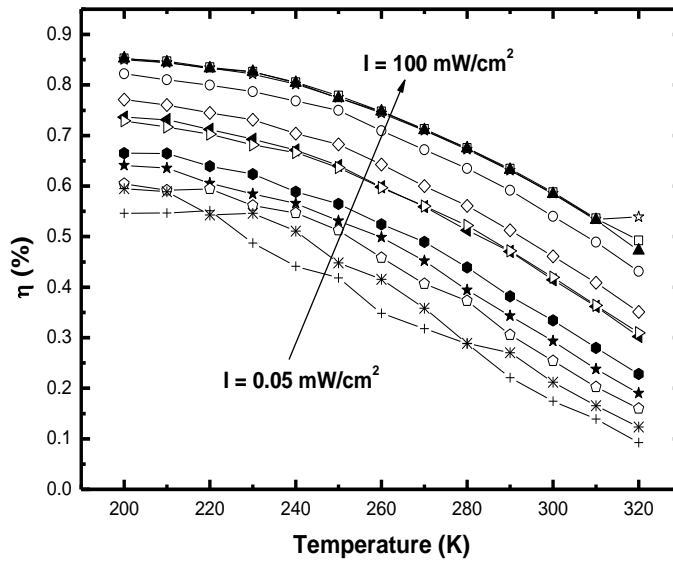


Figure 1: Temperature dependence of conversion efficiency at different illumination intensity $I = 0.05 \text{ mW/cm}^2$ to $I = 100 \text{ mW/cm}^2$

Using equation 2, figure 2 is derived by fitting open circuit voltage as a function temperature to the plot of illumination intensity dependent V_{oc} versus T , and assuming that A , J_{sc} and J_{oo} are independent of temperature, a linear extrapolation to $T = 0 \text{ K}$ gives an activation energy $E_a =$

0.79 eV. As reported elsewhere [9, 10], the activation energy value is close to the $\text{Pb(OH)}_x\text{S}_y$ band gap $E_a = 0.85$ eV. From this analysis, it follows that $E_a \approx E_g$ indicating that recombination mechanism in this type of device takes place in the bulk of the absorber material, also, it can be deduced that the band gap of the chemical bath deposited $\text{Pb(OH)}_x\text{S}_y$ can be engineered for further widening. These results corroborate earlier findings by Koenenkamp and Hoyer [13].

The temperature dependence of the diode ideality factor A when the solar cell is characterized both in the dark and under illumination is shown in figure 3.

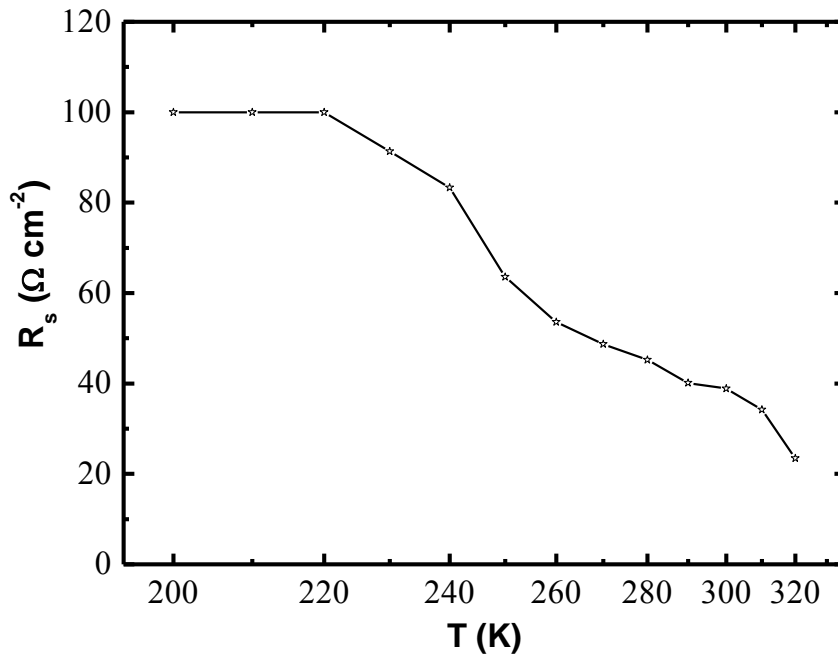


Figure 2. Temperature dependence of series resistance of eta solar

The ideality factor of the eta solar cell is observed to decrease as the temperature increases. In the dark the ideality factor is given by $6.9 \leq A \leq 10.1$, while under illumination it is given by $1.2 \leq A \leq 1.6$. The temperature behavior of the ideality factor in the dark indicates that recombination mechanism of eta solar cell is dominated by tunneling process while under illumination the charge carrier recombination is thermally activated since there is observed temperature dependence [5, 12]. It can also be deduced from the observation that ideality factor decreases as the temperature increases from ~ 1.6 K at 200 K to ~ 1.0 K at 200 K showing that recombination occurs through exponentially distributed energy recombination levels. The values of ideality factor at high temperature under illumination shows the recombination occurs through shallow levels, while at low temperatures deep levels are involved in the recombination.

Lastly, figure 4 shows the temperature dependency of conversion efficiency. The conversion efficiency is observed to vary inversely with temperature at different illumination intensities. The results shows that temperature and illumination intensity have strong influence on the conversion efficiency of the eta solar cell with the highest values being highest at low temperature of 200 K with efficiency increasing from 0.54% to 0.85%.

5. Conclusion

The activation energy of the $\text{TiO}_2/\text{In}(\text{OH})_x\text{S}_y/\text{Pb}(\text{OH})_x\text{S}_y/\text{PEDOT:PSS}$ eta solar cell has been found to be approximately equal to band gap of the absorber material indicating that the band gap can be engineered for further widening. Analysis of the solar cell ideality factor shows that recombination by tunneling process dominates in the solar cell in the dark while under illumination it is thermally activated and takes place in the bulk of the absorber material at high temperatures, but at low temperature it takes place in the shallow levels. Lastly, illumination intensity and low temperature have been found to have strong influence on the conversion efficiency of the eta solar cell device.

References

- [1] S. Siebentritt, K. Ernst, C-H. Fischer, R. Koenenkamp, and M. Ch. Lux-Steiner, Proc. 14th Eur. Photovoltaic Solar Energy Conf. Exhib., Barcelona, Spain, 1997, p. 1823.
- [2] I. Kaiser, K. Ersnt, C-H. Fischer, R. Koenenkamp, C. Rost, I. Sieber, and M. Ch. Lux-Steiner, Sol. Energy Mater. & Sol. Cells **67**, 26 (2006).
- [3] G. Larramona, C. Chone, A. Jacob, D. Sakakura, B. Delatouche, D. Pere, X. Cieren, M. Nagina, and R. Bayon, Chem. Mater. **18**, 1688 (2006).
- [4] B. O'Regan and M. Gratzel, Nature, **353**, 8720 (1990).
- [5] R.J. Musembi, M. Rusu, J.M. Mwabora, B.O. Aduda, K. Fostiropoulos, and M. Ch. Lux-Steiner, Physica Status Solidi, **205** (7), 1713 (2008).
- [6] K. Ernst, R. Engelhardt, K. Ellmer, C. Kelch, H. J. Muffler, M. Ch. Lux-Steiner, and R. Koenenkamp, Thin Solid Films, **387**, 26 (2006).
- [7] A. Wahi and R. Koenenkamp, Proc. 11th Photovoltaic Solar Energy Conf. , Montreux, Switzerland, (1992), p. 714.
- [8] I. Kaiser, K. Ernst, C-H. Fischer, C. Rost, I. Sieber, M.Ch. Lux-Steiner, and R. Koenenkamp, Sol. Energy Mater. & Sol. Cells, **67**, 89 (2001).
- [9] R. Bayon, R. Musembi, A. Belaidi, M. Bär, T. Guminskaya, M. Ch. Lux-Steiner, and T. Dittrich, Sol. Energy, Mater. & Sol. Cells, **89**, 13, (2005).
- [10] R. Bayon, R. Musembi, A. Belaidi, M. Bär, T. Guminskaya, M. Ch. Lux-Steiner, and T. Dittrich, Comptes Rendus Chimie, **9**, 730, (2005).
- [11] V. Nadenau, U. Rau, and A. Jasenek, J. Appl. Phys., **87**, 584, (2000).
- [12] M. Rusu, W. Eisele, R. Wurz, A. Ennaoui, M. Ch. Lux-Steiner, T.P. Niesen, and F. Karg, J. Phys. Chem. Solids, **64**, 2037, (2003).
- [13] R. Könenkamp and P. Hoyer, Appl. Phys. Letter, **E14**, 219, (1995).