**A comparison of the effect of CdCl2 and MgCl2 processing on the transport properties of n-CdS/p-CdTe solar cells and a simple approach to determine their back contact barrier height**

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**Abstract**

A simple approach, which can estimate the barrier height of non-Ohmic Au/CdTe contact for CdS/CdTe solar cell by using its temperature dependent forward biased current-voltage data, is explained. The method involves modelling the forward  characteristics using a double exponential expression for the main junction and by a reverse biased Schottky barrier for the back contact. Cells processed with both CdCl2 and MgCl2 are compared, with the current transport phenomena in both kinds of cells being analysed. Performance loss due to limitation of the forward bias hole current, and its dependence on the post-deposition chloride processing, is also discussed. The forward current transport is mainly dominated by recombination at CdS/CdTe interfacial region with pronounced tunnelling effects. Classical Schottky-type conduction, as described by the Richardson-Schottky formula, is a good fit to the reverse biased current-voltage behaviour of Au/CdTe junction approximately above 240 K. However, below than this temperature, the current limiting effect due to the increasing substantial effects of interfacial defect states can be satisfactorily explained by Bardeen’s model for a modified Schottky type barrier at Au/CdTe interface

**Keywords:** Current transport; Solar cells; CdS/CdTe solar cell; Barrier height

1. **1ntroduction**

Research and development studies on CdTe/CdS polycrystalline heterojunction solar cells have received a considerable attention because of their recent increases in performance and also their reliability and potential for low cost production [1]. A number of laboratories reported efficiencies above 15 % for cm2-scale laboratory cells [2] with the highest efficiencies reported now surpassing 21% [3]. Despite these impressive cell efficiencies, there are still unsolved problems, particularly understanding of the exact effect of post deposition process with chlorides (CdCl2, MgCl2, NaCl etc.,) on interfacial and/or bulk defect states linked to the recombination-generation mechanisms at CdS/CdTe interface, and also on the Schottky like ‘back contact’ potential barrier i.e. the metal/CdTe contact.

It is well known that high efficiency CdS/CdTe solar cell fabrication process requires the CdCl2 treatment that has been in almost universal use for over 25 years. However Major et. al., [4] recently demonstrated that CdCl2 may simply be replaced with a non-toxic and cheap material, MgCl2 in the fabrication process without affecting the conversion efficiency of a typical cell. So far the comparative studies of chloride-based post deposition processing effects were mostly focused on the analysis of external quantum efficiency (EQE), estimation of back contact barrier height, room temperature capacitance profiling and on microstructure [4,5]. Thus, a detailed study of the comparative effects of CdCl2 and MgCl2 through current transport properties of the hetero-interface and understanding of the electrical behaviour of the back contact region remains un-investigated, even though it has the potential to reveal efficiency limiting mechanisms in CdTe solar cells.

The dc characteristics of a typical CdS/CdTe solar cell with a back contact barrier can usually be modelled by in-series back-to-back connected n-CdS/p-CdTe and Schottky like p-CdTe/metal interfaces. This approach allows simple measurements, including temperature dependent current-voltage () to identify the dominant electrical transport mechanisms in the solar cell and also the loss mechanisms due to minority carrier flow through the back contact [6,7]. The back-to-back diode model developed by Stollwerck and Sites [8] is frequently used to extract the value of back contact barrier height from dark data for CdTe and CIGS based solar cells by assuming thermionic emission to be the dominating mechanism at semiconductor metal interface. The other commonly used method proposed by Bätzner et. al.,[9] is analogous – if it assumed that transport over the back contact barrier is dominated by the thermionic emission, then the exponentially varying part of series resistance, *Rs*(*T*) determined at forward bias above *Voc* may then be used to estimate the back contact barrier height which is itself a fitting parameter.

In this contribution, we study the electronic properties of the interface regions in two different sets of SnO2:F/ZnO/CdS/CdTe/Au devices that were post-deposition processed with either CdCl2 or MgCl2 . The method used is temperature dependent dark current-voltage analysis. First, we present an alternative and conveniently simple procedure to estimate the back contact barrier height from characteristics which is verified by comparison with the methods in the literature. In the second part *J* - *V*: *T* data for both MgCl2 and CdCl2 treated cells are compared in an analysis using the two diode and classical Richardson-Schottky equations. The behaviour of device fit parameters with temperature was used to suggest electronic loss mechanisms, both at n-CdS/p-CdTe and the CdTe/Au interfaces.

1. **Experimental**

Small area (0.25 cm2) glass/SnO2:F/ZnO/CdS/CdTe/Au solar cells were prepared in the Stephenson Institute for Renewable Energy at University of Liverpool (UK). The devices were fabricated in the superstrate configuration on commercial soda lime glass substrates (Pilkington TEC10) coated with fluorine doped tin oxide. Radio-frequency sputtering was used to deposit an undoped 100-nm ZnO ‘buffer’ layer onto the fluorine-doped tin oxide by reactively sputtering from a Zn target in the presence of oxygen. A 120-nm-thick CdS layer window layer was then deposited by radio-frequency sputtering at a substrate temperature of 200°C in Ar ambient by using a power of 60 W. The CdTe absorber layer was deposited via close space sublimation deposition, using a custom all-quartz deposition chamber manufactured by Electro-Gas Systems Ltd. Deposition was carried out at source and substrate temperatures of 615°C and 520°C, respectively. Following CdTe deposition, the samples were submerged in a nitric-phosphoric acid etch solution for 15 s to create a Te-rich back surface onto the CdTe layer. Then the CdTe surface was coated with CdCl2 or MgCl2 before annealing in air for 20 - 40 mins at 420°C. The device structure was completed by the evaporation of Au as a back contact to the post-deposition processed CdTe layer. Further details of the fabrication steps are described elsewhere [4].

The illuminated *J* – *V* measurement was performed under an AM1.5 spectrum at 1,000 Wm-2 using a TS Space Systems solar simulator. The photovoltaic parameters for the investigated solar cells are given in Table 1. The temperature dependent dark current density – voltage () measurements were carried by using a computer controlled Keithley source meter at the University of Liverpool, UK in a Janis closed cycle cryostat in the temperature range 70 – 330K.

**Table 1.** Photovoltaic parameters extracted from JV measurements for cells processed with MgCl2 and CdCl2 examined in this work.

|  |  |  |
| --- | --- | --- |
|  | MgCl2 | CdCl2 |
| Voc (V) | 0.82 | 0.76 |
| Isc (mA/cm2) | 26.5 | 25.0 |
| FF (%) | 56.0 | 54.5 |
| η (%) | 12.2 | 10.4 |

1. **Results and Discussion**

**3.1 Analysis of dark JV temperature dependent behaviour**

The temperature dependent dark forward *J* characteristics of typical CdS/CdTe solar cells processed with MgCl2 and CdCl2 are illustrated in Fig.1 (a) and (b) respectively. Two distinct regions can be recognised from these figures, one is due to exponential dependency at low and intermediate voltages and the other is due to roll-over effect caused by the reduced rate of increase of device current at higher voltages related to the back contact barrier. Excluding other sources of series resistance this clearly suggests that a forward bias applied to a typical device drops both over the hetero-interface and the back contact region. These voltage drops will be referred to as and respectively. In fact, as the thickness of CdTe layer is ~4 µm, the depletion regions of both the CdS/CdTe and CdTe/Au interfaces may be assumed to be spatially separated and that they do not interfere with each other. Thus, for the opposing CdS/CdTe and CdTe/Au diode combination, the net current through a typical CdS/CdTe solar cell can be expressed as:

 (1)

Moreover, a description of the dark forward current flowing through the n-CdS/p-CdTe interface should include series () and shunt resistance () effects,

 (2)

where ** stands for the portion of applied voltage over the CdS/CdTe junction, is the diode ideality factor, and  is the reverse saturation current density at the *p*-*n* interface.

It is well known that the current limiting effect seen in characteristics at high forward bias is limited mainly by the hole current flow through the CdTe/Au contact. The effect is usually explained by thermionic emission [6] but it is also a reasonable assumption that a portion of the applied voltage may result in the lowering of the Coulombic potential barrier at CdTe/Au interface [10]. Therefore the current-voltage behaviour of a reverse biased CdTe/Au junction should be described well



 **Figure 1.** The dark characteristics of CdS/CdTe solar cells processed with (a) MgCl2 and (b) CdCl2 at various temperatures. The solid and dashed lines correspond to the fits to Eq. (4) at low and intermediate voltages and to Eq.(5) at higher voltages respectively.

by classical Schottky-type conduction - and therefore the back junction current may be expressed by the Richardson-Schottky formula [11],

 (3)

where is the voltage drop over the back contact interface,  is effective Richardson constant,  is the width of the interfacial depletion region,  is the Schottky coefficient, = and  the Schottky barrier height.

In order to identify the separate contribution of the back contact current to the main diode current, the temperature dependent log *J* and curves were plotted and examined using the classical models expressed by Eqs. (2) and (3). As seen in Fig.1 (a) and (b), at low and intermediate voltages the temperature dependent characteristics can be successfully fitted to a double diode equation having significant series , and shunt resistance effects up to a voltage value at which the roll-over effect is start to seen using the equation;

 (4)

The indices 1 and 2 stand for the first and the second diodes representing low and intermediate voltage regions, respectively. We have noticed that log *J* variations (not shown here) give visually good linear characteristics over the high voltage region over which the back contact effect is appeared. The values for  and  were determined from the intercept of linear variations on the current axis and from the slopes of the linear portions of log *J* characteristics, respectively. The fit of Eq. (3) onto the experimental data over this high voltage region is also illustrated in Fig.1 (a) and (b) by using extracted,  values and its revised form as;

 (5)

It should be noted that the solid and the dashed lines represent the fully compatible fits to Eqs. (4) and (5), respectively as it is seen clearly on both Fig. 1 (a) and (b). In order to have a better understanding of the effect of CdCl2 and MgCl2 processing on the electronic properties of the space charge layers of both CdS/CdTe and CdTe/Au interfaces and also to estimate the barrier height of Schottky like back contact; temperature dependent fit parameters are examined in more detail as follows in the next section.

**3.2 A simple approach to estimate the value of Au/CdTe barrier height**

As it is seen from Fig.1, Schottky-like conduction due to reverse biased CdTe/Au back interface seems to have important role under high forward bias. The expected lowering effect of the Coulombic potential barrier at CdTe/Au interface could possibly be related to the Schottky barrier height. Therefore first the values of pre-exponential current factor values (of Eq. (3)) were determined from almost linearly varying characteristicsover the roll-over region and then was plotted as a function of temperature as it was illustrated in Fig. 2 (a) for both devices. Essentially, we expect from these visually good linear Arrhenius plots that the proposed route for the back current mechanism is seems to play a relevant role particularly above than 240 K. From the slopes of these linear variations back contact barrier heights () were estimated as about 0.40 eV and 0.44 eV for MgCl2 and CdCl2 processed devices, respectively.

In an attempt to conform the validity of the proposed approach the well-known methods developed by Stollwerck and Sites [8] and Bätzner at al., [9] were also applied. At first, the value of back contact saturation current density was estimated from the intercept point of the pre-rollover and the post-rollover slopes of characteristics at each temperature ranging from 70 K to 330 K according to the model proposed by Stollwerck and Sites [8]. Then the estimated values were plotted as a function of temperature as it is also seen in Fig.2 (a) for comparison. It is clearly seen from this figure that both methods display almost the same slopes and thus the samevalues approximately above than 240 K for both solar cells.

Secondly, the other common method proposed by Bätzner at al., [9] was applied. This method indicates that if the current transport over back contact barrier is dominated by the thermionic emission mechanism then the dark characteristics can be fitted to an ordinary single diode equation having parasitic resistance contributions as expressed by Eq. (2). Thus, the temperature dependence of the fitted series resistance values could comprise the separated components indicating ohmic resistance and an exponentially varying part for the contribution due to back contact interface as,

(6)

where is the Ohmic resistance, is the temperature coefficient of the ohmic part and stands for a fitting parameter. The temperature dependent behaviour of data, estimated from fit of double diode equation; Eq. (4), to the data in the intermediate voltage region at temperatures around 220 K are illustrated in Fig.2 (b) for both solar cells. As can be seen in this figure, all estimated  values were likewise in extremely well accordance with those determined by using the proposed method for both solar cells in this work.

With the above results, it is obvious that the method proposed here offer an attractive, simple and reliable alternative way with the perfect accuracy for the estimation of  values. Also these mighty

 **Figure 2.** Richardson plots and temperature dependence of the series resistance of MgCl2 and CdCl2 – processed solar cell devices. (a) vs. characteristics and the fits to the experimental data. (b) log –characteristics and their fit to Eq. (6).

**3.3 The current transport at back contact**

Through more in-depth analysis of the temperature dependant J-V behaviour, we are able to make an assessment of the current transport mechanisms at the back contact. Through analysis of the Schottky coefficient we can compare the dominance of interfacial defect states on the back contact. The theoretical value of the Schottky coefficient expressed in Richardson-Schottky formula (Eq. (3)) can be calculated as,

= 1.189 x10-5 V1/2 m1/2 (7)

where  = 10.17 is assumed for CdTe. Using values evaluated at 300 K (2.81 V-1/2 and 2.1 V-1/2) and  (= ) values estimated from capacitance values (6.1 nF and 2,67 nF) measured at 300 K, 0.9 V and at 1 MHz frequency, the values for experimental Schottky coefficient (= ) were calculated to be about 4.41x10-5 V1/2 m1/2 and 4.99x10-5 V1/2 m1/2 for MgCl2 and CdCl2 processed devices respectively. These values agree with the theoretical value given by Eq.(7) to within a factor of four or five. The reason for this difference may well be due to the approximated width of the back depletion contact region. A more larger values ( ~27 nm and ~48 nm for MgCl2 and CdCl2 processed devices, respectively) can be predicted for the precise accordance with the theoretical value by using (= ). However this diversity presumably suggests that the role of defect states in the back contact depletion region via the charge transport particularly over the rollover could be substantial.

It is clearly seen in Fig.1 (a) and (b) that as the measurement temperature is lowered, the rollover effect is found to occur gradually toward lower bias voltages. The results of analytic simulations reported by Demtsu and Sites [6] have also indicated the presence of this behaviour linking with the increase in the back-barrier height at CdTe/Au interface. However, the back contact barrier height values were found to decrease gradually to about zero with the decrease of temperature below 240 K, as it is implied by Fig.2. (a). This clearly suggests that, the proposed model of Simmons could need to be modified comprising the increasing substantial effects of interfacial defect states [12] particularly below than 240 K. The model proposed by Bardeen [12] can be used to explain the perceived relative contributions of localized states at back contact interface for devices under consideration. According to this model, the Fermi level is pinned due to the energy states at the interfacial layer of a Schottky diode and thus height of the barrier decreases linearly with the applied electric field to the interface. Therefore the reverse bias current given by Eq. (3) at CdTe/Au interface can be rewritten as [13],

 (8)

In this equation the modified Schottky constant  is related to density of interfacial states (), thickness), permittivity () and the charge density () in the depletion layer at metal/semiconductor interface. To identify the presence of this mechanism in both devices the temperature dependent values forwere estimated by using the high frequency (~ 1 MHz) values of the density of interface states estimated from capacitance spectroscopy measurements performed at 0.9 V. The thickness of the CdTe/Au interfacial region was estimated as a function of temperature by using capacitance values measured at 0.9 V, 1 MHz frequency and with εi = 3.8. One obtains temperature dependent values as depicted in Fig.3. Although the behaviour of the reverse current over back contact interface of both solar cells can successfully be modelled on the basis of Simmons’ model for the classical Schottky type conduction, visually good fits of theoretically and experimentally (=) estimated values indicate Bardeen’s model for a modified Schottky type junction describes the current route well for both solar cells approximately below 240 K.

For CdCl2 processed device, the evidence of a sharp declined value of  and charge density can be taken as the evidence of a trapping level. A good agreement between theoretically and experimentally estimated values approximately above 240 K indicates that the localised defect states still limits the back contact current transport in this device.

For MgCl2 processed device, although the presence of thick layer due interfacial defect states can be addressed as the probable source of dominant route for the current transport, one can suggest the decrease its dominance nearly above 240 K. Thus, one can safely suggest that classical Simmons’ Schottky-type conduction model is valid for T > 240 K.



**Figure 3.** Thevariation of Schottky constant,, and density of density of interfacial states,, with temperature for both CdCl2 and MgCl2 – treated CdTe solar cell devices. The fit line for the experimental values of uses Eq. (8).

With the above results, it is obvious that interface states have pronounced effect onto the current transport across back contact interface particularly for the CdCl2 processed device. The relatively high values of predicted charge densities (see Fig. 3) could probably exhibit considerable concentration of defect states probably due to surface preparation [4].

**3.4 Evaluation of forward current by means of a double diode model**

As well as the back contact interface it is also possible to assess the current transport mechanism at the heterojunction via temperature dependant *J-V* analysis. The dominating conduction mechanism at n-CdS/p-CdTe hetero interface for the solar cells under investigation was analysed by dividing the *log* vs **curves into two approximate voltage regions; diode 1: 0.2V > V > 0.4 V and diode 2: 0.4V < V < 0.8 V (see Fig.1). The temperature dependence of the estimated fit parameters for **,  and the parasitic series, , and shunt, , resistances are shown in Figs 4 (a - c).

For diode 1;  values are almost constant with temperature and  values indicate a slight decrease from 4.4x10-8 A/cm2 and 8x10-8 A/cm2 to about 4 x10-8 A/cm2 and 2.4x10-8 A/cm2 with decrease in the temperature from 330 K to 70 K for MgCl2 and CdCl2 processed devices, respectively. As expected, the value of the ideality factor was found to strongly dependent on the temperature and have values  >> 2 for both devices. In addition, this region appears almost linear on a log *I* – log *V* plot implying ∝ (do not shown here) behaviour where is almost unvaried at about 0.94 for the temperature region considered. All these results have suggested that tunnelling plays important role in the current transport. However the presence of high density of interfacial defect states at CdS/CdTe hetero-interface is known to be particular importance in CdS/CdTe solar cells because of the large lattice mismatch. Thus the temperature independent nature of power law dependence may possibly indicate also that the distribution of defect states at CdS/CdTe interface stays invariant with temperature. However their distribution may vary rapidly with energy at hetero-interface [14].



 **Figure 4.** (a)Diode ideality factor as a function of temperature and the fits to . (b) The dark current pre-exponential terms as a function of temperature. The inset shows the corrected Arrhenius plots of the saturation current densities for both solar cells. (c) The temperature dependent variation of fitted parasitic series, and shunt resistance parameters. The inset shows the Arrhenius plots for for both solar cells.

Also, as it is seen in Fig. 4(c) that relatively high values can be estimated by fitting the experimental data to the double diode expression given by Eq.4 for both devices. This possibly reflects the fact that in addition to the contribution due to the back contact interface, a thin interfacial layer proposed to exist near to the CdS/CdTe junction interface could also be a major source to these relatively high estimated values. Thus, this also suggests that the current could be substantially limited by the high resistivity of CdS/CdTe interfacial region in this low biased region for both solar cells.

As it is seen in Fig. 1, approximately below than 220 K the voltage dependence of diode current indicates the dominance of current routes solely due to diode 1and the Schottky-like back contact for both solar cells. However above than 220 K, the contribution due to diode 1 gradually decreases and diode 2 gradually increases as temperature increases. Therefore for *T* > 220 K, the current through the typical device is be determined by diode 2 in the voltage range 0.3 V to about 0.8 V.

For diode 2; as shown in Fig.4 (a) and (b), the temperature dependent variations of both  and  are indicative of two different transport mechanisms approximately below and above than 250 K. For temperatures above than 250 K, the log - 1/T variations are seen to be linear with activation energies of about 0.57 eV and 0.59 eV. And the ideality factor values are nearly constant at about 1.74 and 1.85 for MgCl2 and CdCl2 processed devices, respectively. All this indicates that thermally activated phenomenon dominates the transport. Recombination at hetero interface is known to be particular importance in CdS/CdTe solar cells because of the high density of interface states as proposed above.

For a typical asymmetrically doped heterojunction, pure interface recombination dominated current transport determines that the value of  lies between 1 >  > 2 and depends on the ratio [], where and  are the donor and acceptor concentrations and  and are the dielectric constants of n and p-type regions respectively [15]. Also the product  should be around the built-in voltage  = 1.18 eV of the junction. However the corresponding product was found as 0.99 and 1.09 for MgCl2 and CdCl2 processed devices, respectively.

If depletion region recombination dominates thenvalues may also vary between 1 and 2 and the slope of the log () vs.  plot must yield an activation energy approximately equal to the half of the band gap of the absorber layer [15]. The value of activation energies were calculated as about 0.53 eV and 0.50 eV from the slope of the log () vs.  characteristic (do not shown here) for MgCl2 and CdCl2 processed devices, respectively. The dominance of depletion region recombination mechanism seems doubtful because these values are smaller than. Although these results seem to eliminate the possibility of interface recombination, the relatively low values for activation energies and current densities, and the apparent high density of interface states, all indicate interface state recombination is most likely for both devices. However, the comparably lower  and  values suggest relatively lower density of defect states for the MgCl2 processed device. This could also be one of the reasons for the better photovoltaic performance obtained for this device as compared to the CdCl2 processed one.

For temperatures below than 250 K, Jo varies almost linearly with temperature (not shown here), and >> 2 indicating a pronounced contribution of tunnelling to the thermally activated transport across the junction. The forward current density without parasitic effects in region diode 2 can be expressed by:

 (9)

where  is the activation energy and  a pre-factor which depends on the transport mechanism. The value of the activation energy  can be deduced from experimental data by reorganising Eq. (9) as, . As it is seen in the inset of Fig. 4(b), the value of activation energy for both solar cells  can be calculated from the slope of a linear plot of  -  as about 1.18 eV. This value is smaller than the band gap energy of absorber CdTe. Hence, it is likely that the recombination process could still be governed by the heterojunction interface and  represents the interface barrier height  [16]. Tunnelling of holes from the bulk of the absorber into the interface states and subsequent recombination with electrons available in the buffer layer leads yields the temperature dependence of the diode ideality factor as, where  is the characteristic tunnelling energy measuring the amount of tunnelling contribution to the recombination process.

The temperature dependence of diode ideality factor for regions 1st and 2nd were plotted in Fig. 4 (a) and found that the experimental data fits very well on the theoretical expression with tunnelling energies of about meV and 33 meV for MgCl2 and CdCl2 processed devices, respectively. Thus one can suggest that tunnelling enhanced recombination at CdS/CdTe interface explains the dominant current flow in region diode2 for both solar cells.

Variation of both parasitic resistances with temperature as estimated by fitting the experimental data to Eq.4 are all illustrated in Fig. 4 (c). The value of is constant at about 25x104 cm2 and 4x104cm2 for MgCl2 and CdCl2 processed devices respectively. The presence of relatively high values can also be attributed to the substantial contribution of the thin layer of defect states placed at or near to CdS/CdTe interface and/or to the active role of tunnelling mechanism as proposed above.

For *T* > 180 K, the exponentially varying – *T* characteristics as observed in Fig. 4. (c) can be linked to the increasing contribution of classical Schottky-type conduction mechanism across the CdTe/Au interface with increase in the measurement temperature as proposed in section 3.2. Above ~220 K, the temperature dependencies of the devices are very similar indicating the dominating contribution of series resistance is indeed due to the CdTe/Au interface and the same current transport mechanism across the back contact interface.

Two different temperature dependency regions can be intelligible from Fig. 4 (c), firstly that varies linearly with 1/*T* above than 250 K while secondly it is far from being linear below that temperature. In addition, – plots displays nearly linear behaviour below and above than 250 K indicating two different current routes for these temperature ranges, as expected. The high temperature exponential dependence, with activation energy values : 136 meV and 70 meV, was estimated for MgCl2 and CdCl2 processed devices respectively. As seen in Fig. 4 (c), for T < 250K; the value of has relatively low dependence on for CdCl2 processed device. This behaviour can be explained by the effective role of tunnelling of carriers through defect states in the space charge region of this device. However for the MgCl2 processed device, the value of shows relatively more dependence on indicating non negligible contribution of trapping-detrapping of free carriers through defect states in the space charge region [17]. An exponential dependence on 1/T seen above than 250 K can be attributed to the increase in the number of free carriers thus the recombination related current mechanism for both solar cells. However the continuing linear dependence of on implies a tunnelling mechanism still limits the current transport relatively less in MgCl2 than for CdCl2 processed device.

**4. Conclusion**

A simple approach is proposed for the calculation of the barrier height of a typical non-ohmic CdTe/Au back contact by using the temperature dependent forward biased current-voltage data of typical efficient CdS/CdTe solar cells processed with either MgCl2 or CdCl2. The current limiting roll-over effect seen in characteristics can found to be modelled according to the Schottky-type conduction with pronounced effect of interfacial defect states located at back contact interface. For MgCl2 processed device, Bardeen’s model for a modified Schottky type junction describes the current route well approximately below 240 K. However above ~ 240 K junction current can be estimated by Simmons’ model for the classical Schottky type conduction, indicating decrease in the dominance of interfacial states. For CdCl2 processed device, the interfacial defect states seems to have significant role almost for the whole temperature range thus Bardeen’s model for a modified Schottky type junction can successfully explain the behaviour.

The electronic loss in MgCl2 and CdCl2 processed solar cells was investigated by the use of the temperature dependent behaviour of estimated fit parameters. In the low biased region i.e., diode 1, we have shown that tunnelling current is limited by the high resistivity of CdS/CdTe interfacial region for both solar cells. For the intermediate voltage region (diode 2) and above than 250 K, the temperature dependence of both  and  was found to suggest the presence of interface state recombination mechanism for both devices. However, the comparable lower  and  values revealed relatively lower density of CdS/CdTe interfacial defect states in the MgCl2 processed device. For temperatures below than 250K, tunnelling enhanced recombination at CdS/CdTe interface appeared as the dominating mechanism for both solar cells.

The almost constant behaviour of fitted series resistance values observed for temperatures below 180K was correlated to the substantial contribution of defect states placed at, or near to, the CdS/CdTe interface and/or to the active role of tunnelling mechanisms. However above than this temperature, the increasing contribution of classical Schottky-type conduction mechanism was revealed across the CdTe/Au interface.

The temperature dependence of was found to reflect the presence of two different current routes above and below 250K and it seems that tunnelling plays a more dominant role in the CdCl2 processed device. Above 250K, depending on the increase in the number of free carriers a thermally activated current mechanism with non-negligible contribution from tunnelling has been proposed for both solar cells.

**References**

[1] T. M. Razykov, C. S. Ferekides, D. Morel, E. Stefanakos, H. S. Ullal, H. M. Upadhyaya,

Solar photovoltaic electricity: Current status and future prospects, Solar Energy 85 (2011)

1580–1608.

[2] M. A. Green, K. Emery, Y. Hishikawa, W. Warta, E. D. Dunlop, Solar cell efficiency

Tables (version 43), Prog. Photovolt. Res. Appl. 22 (2014) 1-9.

[3] First Solar Inc., 2014. <http://investor.firstsolar.com/releasedetail.cfm?ReleaseID=828273>.

[4] J. D. Major, R. E. Treharne, L. J. Phillips, K. Durose, [A low-cost non-toxic post growth](http://scholar.google.co.uk/citations?view_op=view_citation&hl=en&user=YMi5CrsAAAAJ&citation_for_view=YMi5CrsAAAAJ:M3ejUd6NZC8C)

[activation step for CdTe solar cells](http://scholar.google.co.uk/citations?view_op=view_citation&hl=en&user=YMi5CrsAAAAJ&citation_for_view=YMi5CrsAAAAJ:M3ejUd6NZC8C). Nature 511 (2014) 334-337.

[5] J. D. Major, L. Bowen, R. E. Treharne, L. J. Phillips, K. Durose. NH**4**Cl alternative to the

CdCl**2** treatment step for CdTe thin-film solar cells, IEEE Journal of Photovoltaics 5

(2014) 386-389.

[6] S.H. Demtsu, J.R. Sites, Effect of back-contact barrier on thin-film CdTe solar cells, Thin

Solid Films 510 (2006) 320–324.

[7] A. Niemegeers and M. Burgelman., Effects of the Au/CdTe back contact on IV and CV

characteristics of Au/CdTe/CdS/TCO solar cells, J. Appl. Phys. 87, 8786 (2000);

10.1063/1.373611

[8] G. Stollwerck, J. R. Sites, Analysis of CdTe back contact barriers, Proceedings of

13th European Photovoltaic Energy Conference, Nice, France, (1995) 2020-2022

[9] D.L. Bätzner, M.E. Özsan, D. Bonnet, K. Büccher., 2000. Device analysis methods for

physical cell parameters of CdTe/Cds solar cells. Thin Solid Films 361-362 (2000) 288-

292.

[10] J. R. Yeargan and H.L. Taylor., 1968. The Poole-Frenkel effect with compensation

present. J. Appl. Phys., 39, 5600-5604.

[11] G. Simmons, 1970. Handbook of Thin Film Technology, L. Maissel and R. Glang, Eds.,

McGraw-Hill, New York, NY, USA, 1970.

[12] S. M. Sze, Physics of Semiconductor Devices 2nd edn , 1981 (New York: Wiley).

[13] A. E. Rakhshani, Y. Makdisi, X. Mathew, N. R. Mathews, Charge Transport

Mechanisms in Au±CdTe Space-Charge-Limited Schottky Diodes. Phys. Stat. Sol. (a)

168, (1998) 177-187.

[14] A. Rose, Space-Charge-Limited Currents in solids, Physical review. 97 (1955)1538-

1544

[15] A. L. Fahrenbruch, R. H. Bube, Fundamentals of Solar Cells. Academic, 1983, New

York.

[16] V. Nadenau, U. Rau, A. Jasenaek, H. W. Schock, Electronic properties of CuGaSe2 based

heterojunction solar cells. Part I. Transport analysis. J. of Applied Physics 87 (2000)

584-593.

[17] S. Banerjee and W. A. Anderson, Temperature dependence of shunt resistance in

photovoltaic devices, Applied Physics Letters 49, 38 (1986); doi: 10.1063/1.97076