

## CdTe/CdS SOLAR CELL PERFORMANCE UNDER LOW IRRADIANCE

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**ABSTRACT:** Solar cells are usually characterised under standard test conditions (STC), which do not resemble realistic operation conditions, especially for indoor applications where the cells operate at much lower irradiances than for outdoor applications. The potential of CdTe/CdS solar cells developed in our laboratory for low irradiance applications typical of indoor use is investigated and compared to conventional cell materials like c-Si and GaAs. Parameters of the IV-characteristics are normalized to the STC values for comparative analysis. The CdTe/CdS cells show a superior relative efficiency and voltage at low intensities than the c-Si and GaAs cells. The CdTe/CdS solar cells with STC efficiencies of around 11 % retain around 8 % efficiency at  $1 \text{ W/m}^2$  and the  $V_{oc}$  remains as high as 600 mV under the same conditions. Together with a low cost production the suitability of these CdTe/CdS cells for indoor application is preeminent, especially for applications requiring high voltages.

This study gives an insight on the irradiance dependent performance of different solar cell materials, as well as explanations of the observed dependencies by analysing the underlying transport phenomena. Therefore irradiance was varied over almost 5 orders of magnitude.

Keywords: Qualification and Testing - 1: CdTe - 2: Indoor application - 3

### 1. INTRODUCTION

Solar cells are usually characterised under standard test conditions (STC) according to the IEC norm [1], which is  $1000 \text{ W/m}^2$  perpendicular irradiance with a AM1.5 global spectrum at  $25^\circ\text{C}$  cell temperature. Although this is a satisfactory procedure, to get comparable cells performance data, it does not represent the real conditions under which solar cells work, either for outdoor or for indoor applications. While for outdoor applications a typical irradiance, of  $50 - 1000 \text{ W/m}^2$  can be expected, indoor applications often have to operate at much lower irradiances, as low as  $0.1 \text{ W/m}^2$ . Human eyes have a logarithmic sensitivity and a fast assimilation of changes in light intensity, which makes it difficult to judge the intensity by the eye alone. A typical office illuminated by fluorescent tubes exhibits an intensity of some  $\text{W/m}^2$  at desk level. Especially in the low intensity region of  $0.1 - 10 \text{ W/m}^2$ , cell parameters can change strongly and are especially dependent on the cell material as well as the production process.

In former studies, on outdoor performance of solar modules in general [2] and on CdTe modules in particular [3], it was found that CdTe modules show a maximum efficiency and  $FF$  for medium irradiances in the range of  $200 - 400 \text{ W/m}^2$ . A more detailed study on outdoor performance of CdTe modules analyses the  $FF$  dependence on irradiance [4]. Suitability of solar cells for indoor applications is investigated comparing 6 different materials [5].

This paper focuses on the low light level performance of HVE CdTe/CdS solar cells in comparison to conventional solar cell materials such as c-Si and GaAs.

### 2. EXPERIMENTAL DETAILS AND RESULTS

The CdTe solar cells have been developed using a high

vacuum evaporation (HVE) process at low superstrate temperature [6]. Typical performance of these cells is in the range of 10 - 12.5 % efficiency (STC). For comparison,  $4 \text{ cm}^2$  c-Si cells from Hamamatsu and GaAs cells from FhG ISE (Germany) were used. IV-measurements were carried out using a halogen lamp. Irradiance intensity was changed by applying screen printing meshes in order to maintain the same spectrum and homogeneity. The cells were shaded with an aperture during the measurements preparation and only illuminated during the short period of measurement to prevent an increase in cell temperature and any so called light soaking effects, which are apparent for thin film solar cells. For CdTe these light soaking effects are generally beneficial since meta stable traps get filled and do not annihilate current by recombination. The error in the absolute efficiency determination for the system is about 5 %. Due to the use of halogen lamps, the spectrum is red weighted and the measurements were not corrected for the spectral mismatch. Since only relative values will be compared in the following, systematic inaccuracies are eliminated.

For the fitting and the simulation of the IV-characteristics a general diode model was used. The fitting was done using a simplex algorithm [7]. The 1-diode model was taken for simplicity and comparability reasons, taking into account that the accuracy of the parameter determination might be lower. However, more advanced models are not applicable for all type of cells, especially for the CdTe cells, which are not suited for a diode-fit when a high back contact barrier is apparent and the IV-characteristics show a pronounced roll over at high forward bias.

In order to compare the irradiance dependent performance of different cell materials the main cell parameters like efficiency,  $V_{oc}$  and  $FF$  will be given as relative values normalized to unity with respect to the STC value.

## 2.1 Diode Model

The IV-characteristics have been fitted to the conventional 1-diode model

$$J(V) = J_{01} \left( \exp \frac{q(V - JR_s)}{nkT} - 1 \right) - J_{ph} + \frac{U - JR_s}{R_p} \quad (1)$$

where  $n$  is the quality factor of the diode,  $k$  the Boltzmann constant,  $T$  the absolute Temperature,  $q$  the electron charge,  $J_{01}$  the dark current density of the diode,  $J_{ph}$  the photo generated current density and  $R_s$  and  $R_p$  the series and the parallel resistances. From the 1-diode model an approximation for the open circuit voltage  $V_{oc}$ , where  $J = 0$  can be derived

$$V_{oc} \approx \frac{nkT}{q} \ln \left( \frac{J_{sc}}{J_{01}} \right) \quad (2)$$

For ideal pn-junctions the assumption can be made that  $n$  and  $J_{01}$  are constant with irradiance  $G$ . Since  $J_{sc}$  can be assumed to be linear with  $G$  for all cells, it follows that

$$V_{oc} \propto \ln(G). \quad (3)$$

## 2.2 Variation of $V_{oc}$ , $n$ and $J_{01}$ with Irradiance

The relative  $V_{oc}$  of the investigated cells normalized to the STC value is shown in Fig. 1. The relative  $V_{oc}$  values of the HVE CdTe/CdS solar cells remain higher than those of the other cells especially at low intensities. At  $0.5 \text{ W/m}^2$  the  $V_{oc}$  is 560 mV, still more than 71 % of the STC value. For indoor applications which should operate under normal office light conditions this means, an average  $V_{oc}$  per cell of 600 - 700 mV should be obtained.

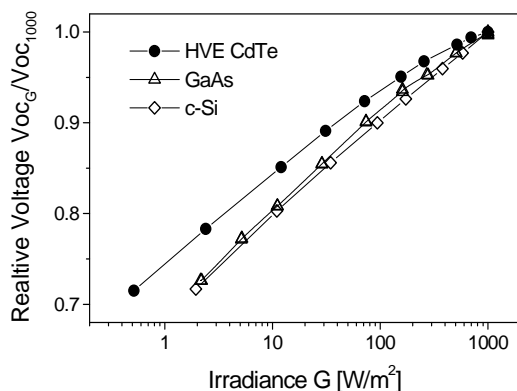


Figure 1: Relative  $V_{oc}$  vs. irradiance normalized to the STC value.

Since the graphs in Fig. 1 are not strictly linear eq. (3) is not fulfilled for any of the cells. This indicates that either the  $n$  or  $J_{01}$  or both depend on  $G$ .

The change of diode quality factor  $n$  with irradiance is shown in Fig. 2. For c-Si cells an increase in  $n$  under lower light levels is evident while  $n$  decreases for GaAs and HVE CdTe cells. According to eq. (2) this causes a decrease in  $V_{oc}$  for GaAs and especially for CdTe in the order of 2,

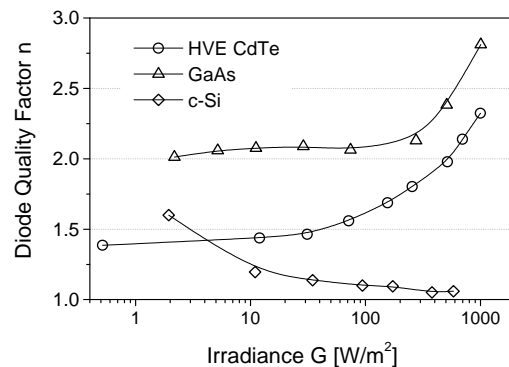


Figure 2: The diode quality factor  $n$  vs.  $G$  extracted from the 1-diode fit of the measured IV-characteristics.

while c-Si should retain a high  $V_{oc}$  value. Instead, the relative  $V_{oc}$  for the CdTe retains the highest value, whereas GaAs and c-Si show comparable behaviour. This leads to the conclusion, that  $n(G)$  is not the sole determining factor for the  $G$  dependent variation of  $V_{oc}$ .

The value of  $n$  is determined by the type of current transport mechanism in the cell. Typically a value of  $n = 1$  is assigned to an ideal transport across the junction according to the Shockley theory, which is diffusion and direct recombination. A value of  $n = 2$  is assigned to predominating defect recombination via mid gap states in the space charge region, i.e. Shockley-Read-Hall (SRH) recombination. Values higher than 2 are possible by multi recombination steps or multi step tunnelling [8].

In case of the HVE CdTe/CdS solar cells, the decrease of  $n$  under lower intensities indicates a change in transport mechanism corresponding to a more ideal junction. Assuming a constant contribution from defect recombination and direct transport via the junction, it seems a tunnelling transport is dominant at higher injection rates, i.e. high irradiance. This is supported by voltage biased QE measurements that evidence the presence of a barrier in the front of the junction [9]. In contrast, the c-Si cells show a near ideal behaviour under STC, whereas in lower injection mode, SRH recombination becomes important.

Since variation of  $n$  does not explain the behaviour of  $V_{oc}(G)$ , it is necessary to further investigate the dependency of the dark current density  $J_{01}$  on the irradiance, see Fig. 3.

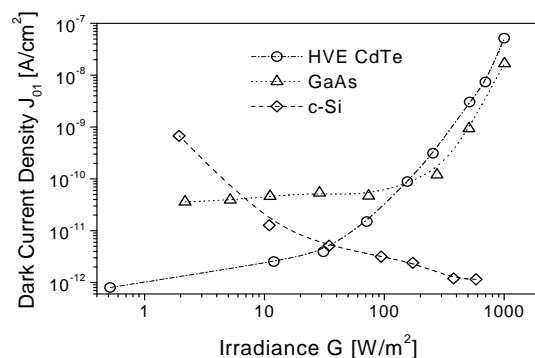


Figure 3: Dark current density  $J_{01}$  vs.  $G$  derived from the 1-diode fit of the IV-characteristics.

For the GaAs and the CdTe cells  $J_{01}$  increases enormously with irradiance, up to 5 orders of magnitude. This is the main cause for a retained higher  $V_{oc}$  at low light levels. It also indicates that the diode quality of the pn junction suffers from a rising  $J_{01}$ , which possibly is due to parasitic currents that become more important for higher injection. The  $J_{01}$  of the c-Si cells in contrast is low at STC and increases towards lower intensities. This compensates the effect of  $n(G)$  on  $V_{oc}$  in the opposite way as for the CdTe/CdS and GaAs cells.

The approximation in eq. (2) excludes the influence of a shunt resistance  $R_p$ , which will become important if  $R_p$  becomes too low. In this case, a low  $R_p$  acts similar to a high  $J_{01}$  and reduces  $V_{oc}$ . This will be analysed in the following.

### 2.3 Variation of $FF$ , $R_p$ and $R_s$ with irradiance

Another important parameter is the fill factor  $FF$ , which determines the efficiency to a great extent. The fill factor is given by

$$FF = (V_{mpp} \cdot J_{mpp}) / (V_{oc} \cdot J_{sc}) \quad (4)$$

the index  $mpp$  denotes the maximum power point (MPP). We can assume that  $J_{mpp}$  - like  $J_{sc}$  - is linear with  $G$  or deviates only minimal from linearity, so it can be neglected here. Then, the  $FF$  is determined by the relation  $V_{mpp}/V_{oc}$ .

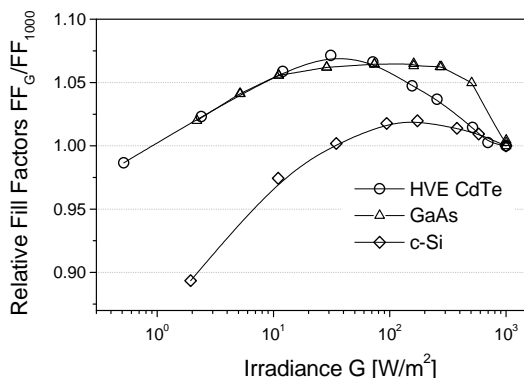


Figure 4: Relative  $FF$  vs. irradiance.

Fig. 4 shows the relative  $FF(G)$  for the investigated cells. It is difficult to get an expression for the irradiance dependence of  $V_{mpp}$ . For irradiances below  $20 \text{ W/m}^2$  the relative  $FF$ s follow the behaviour of the  $V_{oc}$ s. For irradiances from around  $100 \text{ W/m}^2$  to STC the  $FF$ s decrease, which indicates that  $V_{oc}$  increases more than  $V_{mpp}$ . This can be explained by taking the resistances and their influence on the MPP into account. Generally, the  $FF$  is limited by the resistances, when the parallel resistance is too small and the series resistances too big. To deduce the influence of the resistances on  $FF$ , the irradiance dependence of the resistances  $R_p$  and  $R_s$  are shown in Fig. 5.

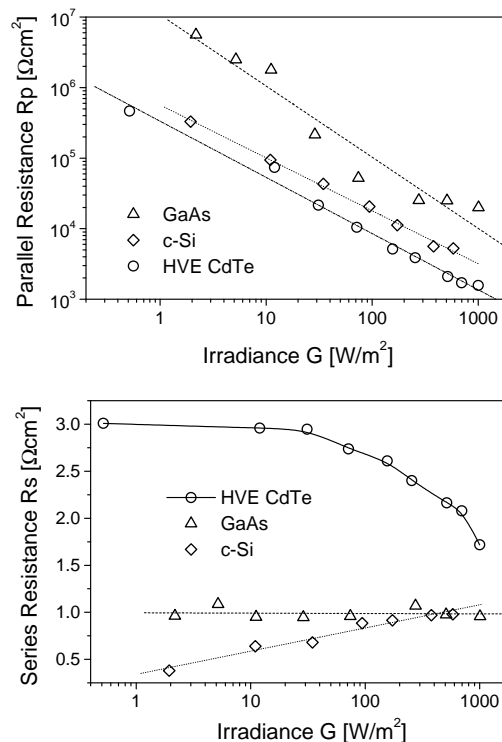


Figure 5: Parallel resistance  $R_p$  (above) and series resistance  $R_s$  (below) vs.  $G$  as extracted from the 1-diode fit of the IV-characteristics.

The irradiance dependency of  $R_s$  shows a different trend for each of the cells, while  $R_s$  for the GaAs cells is constant, it decreases slightly for the c-Si cells and increases slightly for the HVE CdTe/CdS cells towards lower intensities, but all cells show reasonably small  $R_s$ . The fact that the  $R_s$  of CdTe/CdS is higher than for the other cells originates from the transparent oxide front contact, which is a highly doped semiconductor with limited conductivity and not a metal grid.  $R_p$  increases more or less linearly towards lower intensities for all investigated cells. The lower values of  $R_p$  at high intensities cause a limitation of  $V_{mpp}$  around STC. The increase of  $R_p$  towards lower intensities could be due to photoconductivity in the cells. As expected, the naturally defect rich micro-crystalline CdTe shows lower  $R_p$  compared to the mono-crystalline materials.

The efficiency will be determined by the irradiance dependence of  $V_{oc}$  and  $FF$ , since  $J_{sc}$  and  $J_{mpp}$  are linear in  $G$ . The actual behaviour can be seen in Fig. 6. The CdTe/CdS solar cells made with the HVE process show the best relative efficiency and the less decrease in efficiency towards low intensities compared to the other cells. This means basically, that for indoor applications 80 % of the STC efficiency is maintained for  $2 \text{ W/m}^2$ . However, it should be mentioned, that these results might only apply for the specific technologies used for the processing of the investigated cells and could be different for same material cells processed with a different technology.

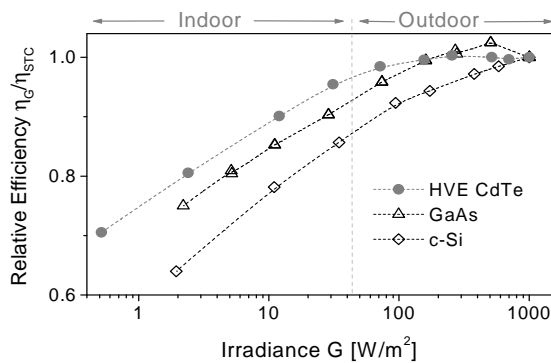


Figure 6: Relative efficiency  $\eta_G/\eta_0$  vs. the irradiance  $G$  for different cell technologies.

### 3. SIMULATION

To illustrate the influence of  $R_s$ ,  $R_p$  and  $J_{01}$  on the voltages and the  $FF$ , a simulation was carried out. The IV-characteristics measured under STC served as a reference to extract the diode model parameters of eq. (1). Varying only one parameter in eq. (1) at a time, modified IV-characteristics have been calculated and the change in  $V_{mpp}$ ,  $V_{oc}$  and their relation, which is proportional to the  $FF$ , were evaluated. The simulation parameters are given in Table I. The calculated IV-characteristic parameters can be seen in Fig. 7.

Table I: Diode model parameters taken for simulation. Parameters varied are indicated in bold.

	Ref.	lower $R_p$	higher $R_s$	lower $R_s$	higher $R_p$	lower $J_{01}$
$R_s$ [ $\Omega\text{cm}^2$ ]	1.8	1.8	<b>3</b>	<b>0.8</b>	1.8	1.8
$R_p$ [ $\Omega\text{cm}^2$ ]	2.4e3	<b>3e2</b>	2.4e3	2.4e3	$\infty$	2.4e3
$J_{01}$ [A/cm <sup>2</sup> ]	2.5e-9	2.5e-9	2.5e-9	2.5e-9	2.5e-9	<b>1.5e-9</b>

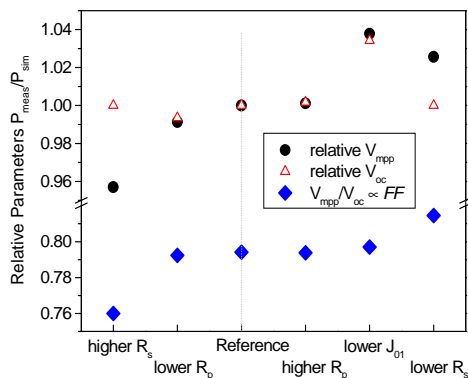


Figure 7: Relative Parameters  $P_{\text{meas}}/P_{\text{sim}}$  of  $V_{mpp}$ ,  $V_{oc}$  and  $V_{mpp}/V_{oc} \propto FF$  for IV characteristics simulated with parameters from Table I.

For the given parameters, changes in  $R_p$  and  $J_{01}$  have similar effect on  $V_{oc}$  and  $V_{mpp}$ . This results in a more or less constant  $FF$ . Only the absolute values of  $V_{oc}$  and  $V_{mpp}$  are changed. Since reference IV-characteristics has already a high  $R_p$  almost no changes occur by simulating an infinite  $R_p$ , i.e.  $V_{oc}$  and  $V_{mpp}$  do not improve. For lower  $R_p$   $V_{oc}$  and  $V_{mpp}$  are decreased, so  $R_p$  acts as a limitation.

Changes of  $R_s$  do not effect  $V_{oc}$  but effect  $V_{mpp}$  strongly. Therefore, the ratio of  $V_{mpp}$  to  $V_{oc}$ , which is proportional to the  $FF$ , is changed strongly. The influence of  $R_s$  on the  $FF$  should be considered when interpreting irradiance dependent measurements, especially for series connections of cells where  $R_s$  may become quite large.

### 4. CONCLUSIONS

CdTe/CdS solar cells are well suited for indoor applications due to their good low irradiance performance. The voltage remains especially high at low light levels. This is favourable for applications that need to provide high voltages even under low irradiance conditions. Since the efficiency retains a high value for low irradiance, i.e. still 8 % for 1 W/m<sup>2</sup>, these type of solar cells are also suited for low cost high power generators, e.g. for consumer electronics operated indoors.

The current transport in the HVE CdTe/CdS cells changes from a SHR recombination dominated transport at low injection levels to a transport dominated by multi recombination and/or tunnelling under STC.

### 5. ACKNOWLEDGEMENTS

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