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SCREEN-PRINTED CdS/CdTe SOLAR CELL OF 12.8% EFFICIENCY FOR AN ACTIVE AREA OF 0.78 cm^2

H. MATSUMOTO, K. KURIBAYASHI, H. UDA, Y. KOMATSU, A. NAKANO and S. IKEGAMI

Wireless Research Laboratory, Matsushita Electric Industrial Co. Ltd., Kadoma, Osaka 571 (Japan)

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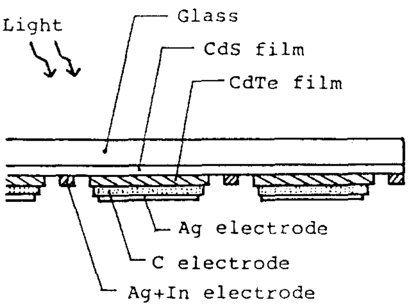
Summary

A screen-printed CdS/CdTe solar cell was produced with improved preparation conditions for the carbon electrode, and the influence of the width of the CdTe layer on the characteristics of the cell was studied. The maximum practical efficiency was obtained for a CdTe layer width of around 5 mm. The fill factor increased with decrease in the width of the CdTe layer, and the maximum fill factor was around 0.6, about 0.1 higher than that reported previously. The improvement in the preparation conditions for the carbon electrode is thought to increase the fill factor. The maximum intrinsic efficiency was obtained for a CdTe layer width of 2 mm and was found to be 12.8% for an active area of 0.78 cm^2. This is the highest value obtained for any thin film type of cell. The values of the diode quality factor n, the reverse saturation current I_0 and the series resistance R_s for the 12.8% efficient cell were 2.2, 2.3×10^{-8} A and 3.8 Ω respectively. The R_s value of 3.8 Ω was much higher than the value calculated by assuming that R_s was determined only by the resistance of the CdS film.

1. Introduction

The CdS/CdTe heterojunction solar cell has a high potential as a solar energy converter. Fahrenbruch *et al.* [1] theoretically estimated the solar conversion efficiency for the CdS/CdTe heterojunction and obtained a value of 17%. Yamaguchi *et al.* [2] made a solar cell by growing a CdS epitaxial layer on a p-type CdTe crystal plate; the highest efficiency obtained was 11.7% for the active area. Tyan and Perez-Albuerne [3] prepared a thin film type of CdS/CdTe solar cell by a close-spaced sublimation technique and obtained a cell of 10.5% intrinsic efficiency.

We have studied the preparation of CdS/CdTe solar cells by a screen-printing method and succeeded in obtaining a cell of 9.0% intrinsic efficiency using a 10 cm × 10 cm borosilicate glass substrate [4]. Figures 1 and 2



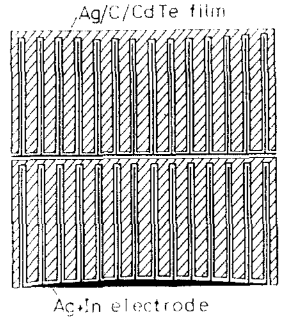


Fig. 1. Cross section of the CdS/CdTe solar cell.

Fig. 2. Print pattern of the CdS/CdTe solar cell. The silver electrode of the bottom cell is connected to the silver plus indium bus-bar electrode of the upper cell by silver paste applied by screen printing and the two cells were connected in series.

show the cross section and print pattern of the cell made on the 10 cm × 10 cm substrate respectively.

In Fig. 2, as the CdTe width decreases, the series resistance of the cell decreases, *i.e.* the fill factor increases. However, the fill factor saturated at around 0.5 even for a CdTe width of 2 mm, as reported in our previous paper [5]. We suggested that it might be necessary to reduce the contact resistances between the semiconductor films and the electrodes to obtain a higher value of the fill factor.

Recently, we found that the addition of 50 - 100 ppm Cu to the carbon electrode effectively raised the efficiency [6]. We assumed that the copper diffused into the CdTe layer during the heat treatment of the carbon electrode and made the CdTe layer p^+ type, reducing the contact resistance between the carbon electrode and the CdTe layer. Therefore, the application of a carbon electrode containing 50 - 100 ppm Cu to a cell whose CdTe layer width is small will raise the fill factor.

In the present work, we investigated the effect of the width of the CdTe layer on the characteristics of screen-printed CdS/CdTe solar cells produced under improved preparation conditions for the carbon electrode and obtained a cell with a 12.8% intrinsic efficiency for a CdTe width of 2 mm.

2. Experimental details

As shown in Fig. 3, 14 cells whose CdTe widths x ranged from 2 to 8 mm were made on a 5 cm × 10 cm substrate. Figure 4 shows an enlarged view of one cell. The CdTe width is x mm. The gap between the two neighbouring CdTe films is 2 mm, and the silver plus indium electrode is attached in this gap. Therefore, an area of $(x + 2)$ mm × 50 mm is necessary for one cell.

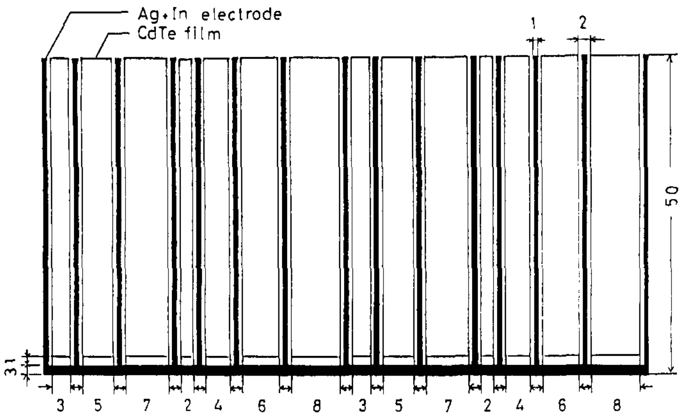


Fig. 3. CdTe pattern for determining the optimum CdTe width. The numerals indicate the dimensions in millimetres.

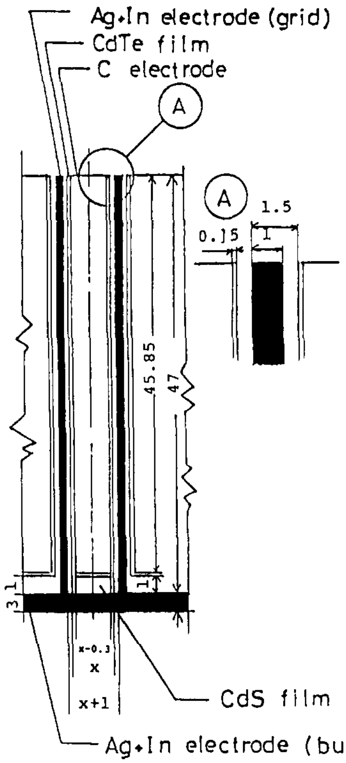


Fig. 4. Enlarged view of one of the cells shown in Fig. 3. The silver electrode is put onto the carbon electrode. The numerals indicate the dimensions in millimetres.

As the p–n junction is formed below the carbon electrode [7], the active area is calculated to be $(x - 0.3)$ mm $\times$ 45.85 mm. So the percentage of effective area is $100 \times 45.85(x - 0.3)/50(x + 2)$. The percentage of effective area increases as x increases.

The preparation conditions for each layer except the carbon electrode were nearly the same as reported previously [4, 5]. The sintering temperatures of the CdS and CdTe films were 690 °C and 620 °C respectively. The specific sheet resistance of the CdS film after the CdTe film had been sintered was between 80 and 120 Ω/□.

In the same way as for the carbon electrode, a carbon paste containing approximately 50 ppm Cu was screen printed onto the CdTe film and heated at about 400 °C for 30 min in an N_2 atmosphere which included about 1% O_2 [6].

The photovoltaic characteristics of each cell were measured using an air mass 1.5 solar simulator (100 mW cm^{-2}).

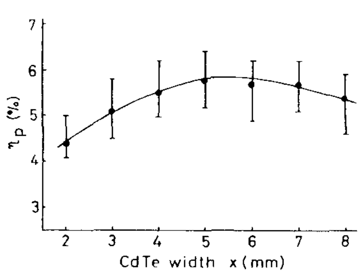
3. Results and discussion

Figure 5 shows the relation between the practical efficiency η_p and the CdTe width x in a cell. The optimum value of x was around 5 mm, the same result reported previously [5], although the absolute value of η_p was higher.

Figure 6 shows the relation between the fill factor and x. The fill factor increased with decrease in x as expected, and the maximum fill factor was around 0.6, about 0.1 higher than the value obtained previously [5]. The improvement in the preparation conditions for the carbon electrode is thought to increase the fill factor [6].

Figure 7 shows the voltage–current (V–I) characteristics of the cell with the maximum intrinsic efficiency η_i which was obtained at the minimum CdTe width of 2 mm as expected. η_i was 12.8% for an active area of 0.78 cm^2, and the open-circuit voltage, short-circuit current and fill factor were 0.754 V, 21.8 mA and 0.606 respectively.

Forward dark V–I characteristics of the 12.8% efficient cell are shown in Fig. 8. The forward characteristics could be expressed by the equation



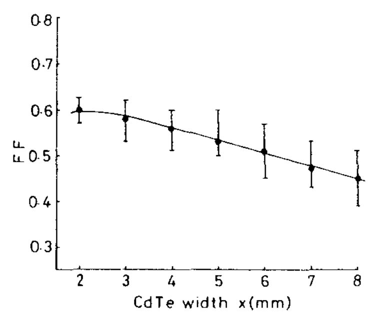


Fig. 5. The relation between η_p and the CdTe width x. The specific sheet resistance of the CdS film is 100 Ω/□.

Fig. 6. The relation between the fill factor FF and x.

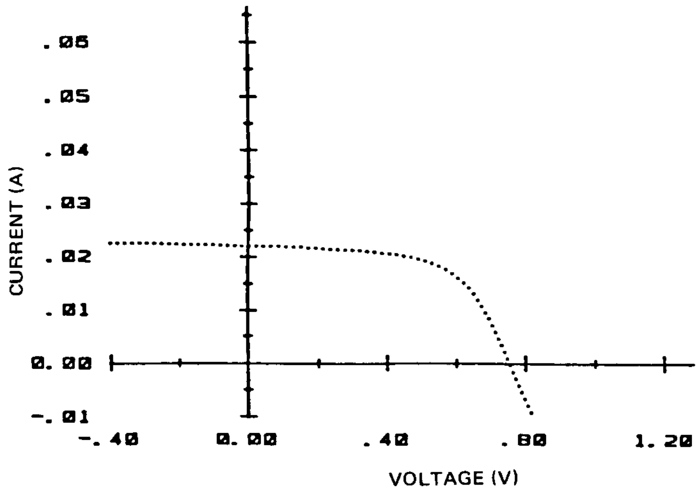


Fig. 7. V–I characteristics of the maximum intrinsic efficiency (area, 0.78 cm^2; V_{oc} = 0.7536 V; I_{sc} = 0.0218 A; P_{max} = 0.009 972 W; fill factor, 0.606; $\eta_{i\,max}$ = 12.78%; V_{max} = 0.5731 V; I_{max} = 0.0174 A).

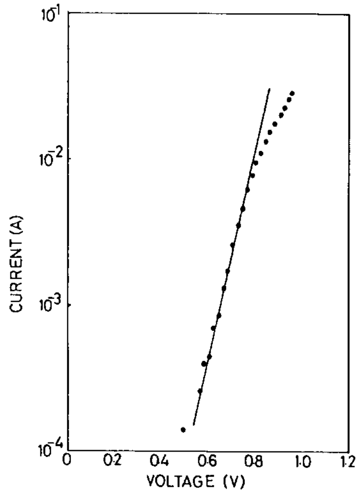


Fig. 8. V–I characteristics for a 12.8% efficient cell in the dark at room temperature. A forward current was obtained when the CdS layer was biased negatively.

$$I = I_0 \exp\left(\frac{qV}{nkT}\right)$$

The values of the diode quality factor n and reverse saturation current I_0 were 2.2 and 2.3×10^{-8} A respectively. The deviation from an exponential relation at high currents in the forward-bias region indicated an R_s value of 3.8 Ω.

The CdS film acts both as a semiconductor and as an electrode. Its sheet resistance ρ_s was about 100 $\Omega/\square$. In order to estimate the influence of

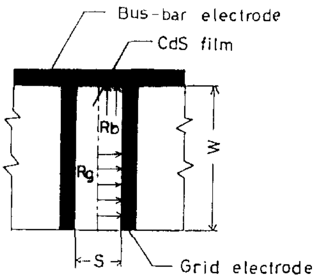


Fig. 9. The solar cell geometry used to estimate the influence of the resistance of the CdS film on the series resistance of the CdS/CdTe solar cell.

the resistance of CdS film, we assumed that R_s was determined only by the resistance R_g that carriers encountered flowing to the silver plus indium grid electrode and the resistance R_b that carriers encountered flowing to the bus-bar electrode on the CdS film. We considered only R_g in our previous paper [5]. To obtain a higher degree of accuracy, however, it is better to consider both R_g and R_b as in this paper.

For the geometry shown in Fig. 9, R_b and R_g are given by [8]

$$R_b = \frac{\rho_s r}{S}$$

and

$$R_g = \frac{R_b r}{2W - r}$$

respectively where r is given by

$$\left(\frac{2r}{S}\right)^2 = \frac{2W}{r} - 1 - 2\left(\frac{W}{r} - 1\right)^2 \ln\left(\frac{W}{W-r}\right)$$

Therefore, we can obtain the values of R_g and R_b by taking ρ_s as 100 Ω/□, W as 47 mm and S as 3 mm for the cell with a CdTe width of 2 mm. R_s can be shown to be given by

$$R_s = \frac{R_g R_b}{2(R_g + R_b)} \tag{1}$$

R_s for the 12.8% efficient cell calculated from eqn. (1) was found to be 0.8 Ω. The difference between the experimental value of R_s (3.8 Ω) and the calculated value (0.8 Ω) is assumed to be due to factors other than the resistance of the CdS film. Analysis of the other factors which increase the value of R_s will be useful in the realization of a higher efficiency cell.

4. Conclusion

We investigated the influence of the CdTe width on the characteristics of a screen-printed CdS/CdTe solar cell produced with the following improved preparation conditions for the carbon electrode: approximately 50 ppm Cu was added to the carbon electrode which was then heat treated at 400 °C for 30 min in an N_2 atmosphere containing about 1% O_2.

The maximum practical efficiency was obtained for a CdTe width of around 5 mm. The fill factor increased with decrease in the CdTe width, and the maximum fill factor was around 0.6, about 0.1 higher than the value reported previously. The improvement in the preparation conditions for the carbon electrode was thought to be the reason for the increase in the fill factor.

The maximum intrinsic efficiency was obtained for a CdTe width of 2 mm and was found to be 12.8% for an active area of 0.78 cm^2. This is the highest value obtained for any thin film type of cell. The values of n, I_0 and R_s for the 12.8% efficient cell were 2.2, 2.3×10^{-8} A and 3.8 Ω respectively. The R_s value of 3.8 Ω was much higher than the value calculated by assuming that R_s was determined only by the resistance of the CdS film. We are now investigating the other factors which increase the value of R_s.

Acknowledgments

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