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Preparation of (n) a-Si : H/(p) c-Si heterojunction solar cells

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Abstract

Heterojunction solar cells have been manufactured by depositing n-type a-Si : H on p-type 1–2Ω cm CZ single crystalline silicon substrates. Although our cell structure is very simple – neither a BSF nor a surface texturing is used – a conversion efficiency of 13.1% has been achieved on an area of 1 cm^2. In this paper the technology is described and the dependence of the solar cell parameters on the properties of the n-type a-Si : H layer is discussed. It is shown that this cell type exhibits no degradation under light exposure.

Keywords: Heterojunction solar cells; Single crystalline silicon substrates

1. Introduction

a-Si : H/c-Si heterojunction solar cells are supposed to be cost-effective devices with high conversion efficiencies. Sawada et al. [1] have presented (p) a-Si : H/(n) c-Si cells ith efficiencies up to 20.0%. P-type crystalline silicon substrates should yield higher efficiencies due to the superior diffusion length of their minority carriers. Kolter et al. [2] have presented an (n) a-Si : H/(p) c-Si cell with an efficiency of 11.1% using 1–2 Ω cm substrates with an Al BSF. Roca et al. [3] presented a cell with 14.3% efficiency on an aperture area of 0.75 cm^2. In both cases extremely pure FZ silicon substrates were used. In this work we focus on (n) a-Si : H/(p) c-Si cells with areas of 1 cm^2 on cheaper CZ substrates.

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2. Preparation of solar cells

Fig. 1 shows the two different structures which were used. Type 1 consists of a p-type c-Si substrate (CZ, 1–2 Ω cm) on which an amorphous n-type a-Si : H or a-Si : C : H layer is deposited. For current collection and reflection reduction a 80 nm thick ITO layer has been deposited on the front side using electron beam evaporation. On the top of the ITO a front grid is applied by evaporating 30 nm Cr and 3 μm Ag. For the back contact 2 μm Al has been used. For the second structure (type 2) an intrisic a-Si : H buffer layer has been inserted between the substrate and the n-type a-Si : H layer.

Prior to any a-Si : H layer deposition the following cleaning procedure has been used:

- 5 min rinsing in acetone,
- 1 min rinsing in 18 MΩ deionized water,
- 2 min etching in ammonia fluoride,
- 1 min rinsing in 18 MΩ deionized water,
- drying with N_2,
- drying on a hot plate for 30 s at 110°C.

It is to mention that we found no evidence for the fact that a better cleaning procedure like the classical RCA cleaning [4] improves the solar cell properties.

After the cleaning the a-Si : H layers were deposited using a three chamber PECVD system. The deposition parameters for the different types of a-Si : H layers are listed in Table 1. The ITO layer has been formed by electron beam evaporation at room temperature and subsequent annealing at 250°C in air as described in [5]. Finally, the front grid and the back contact were evaporated. Special care has been taken to the fact that after the a-Si :H deposition the process temperatures did not exceed 250°C in order to avoid degradation of the a-Si : H layers.

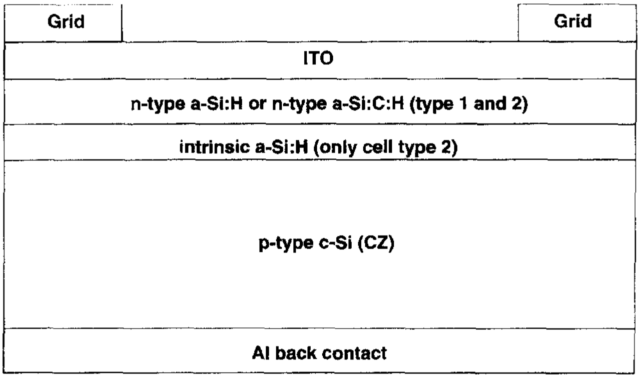

Fig. 1. Cross section of heterojunction solar cells (schematically).

Table 1
Properties of the amorphous silicon layers

Type	Dep.[a] temp. (°C)	Dep. pressure (mTorr)	power Density (mW/cm^2)	Flow PH$_3^b$ (sccm)	Flow SiH$_4$ (sccm)	Flow CH$_4$ (sccm)	Band-gap (eV)	Dark Conduct. (Scm^{-1})
n a-Si : H	350	300	28	12	24	–	1.70	1.9×10^{-2}
n a-Si : C : H	350	300	28	12	24	50	1.83	1.7×10^{-5}
i a-Si : H	300	600	21	–	40	–	1.65	5.7×10^{-11}

[a]substrate temperature ≈ 0.73x deposition temperature. [b]3% PH_3 in SiH_4.

3. Results and discussion

3.1. (n) a-Si : H/(p) c-Si heterojunctions

Fig. 2 shows the dependencies of the solar cell parameters on the thickness of the (n) a-Si : H layer for the simplest cell structure, type 1. The reduction of the thickness results in an increase of the efficiency up to nearly 13%. The main reason for this improvement is the increase of the short circuit current (Fig. 2a). The open circuit voltage remains constant for thicker films and decreases slightly for thin films (Fig. 2b). It should be mentioned that for thicknesses smaller than 5 nm the open circuit voltage drops down to values around 250 mV due to local shunting of the pn-junction by the ITO layer because of the inhomogeneity of the a-Si : H layer deposition. The fill factor of the cells (Fig. 2b) increases from 70% to 73% because the contribution of the a-Si:H layer to the series resistance is reduced.

From Fig. 3 it can be seen that for thinner films the quantum efficiency is enhanced especially in the blue spectral region where the absorption of the a-Si : H films is high. Due to its structural disorder and high doping the diffusion length of the carriers in the amorphous layer is so small that only drift current but no diffusion current can occur. On the other hand because of the high layer doping the penetration depth of the space charge region in the a-Si : H layer is so small even for the thinnest layer that there is no electric field inside the layer. So the amorphous layer acts as a dead layer which does not contribute to the photocurrent. For that reason it has to be as thin as possible. At wavelengths higher than 730 nm the a-Si:H layer is transparent and the quantum efficiency is only determined by the substrate and back contact properties.

To overcome the problem of the strong absorption a-Si : H layers with a higher band gap (see Table 1) were used. With this concept one may get a higher photocurrent and open circuit voltage and thus higher efficiencies. Table 2 lists the properties of such cells as a function of the deposition time. It can be seen that due to the better transparency of these layers the short circuit currents are close to 30 mA even for the thicker films. Like for the cells with smaller band-gap films the open circuit voltage is constant (and slightly higher) for thicker films and decreases for thin films. The main problem of this cells is the low fill factor according to the lower conductivity of this

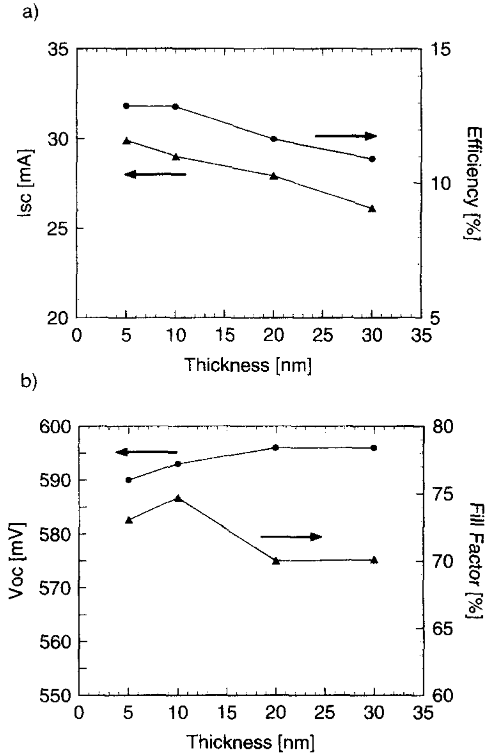

Fig. 2. Characteristics of (n) a-Si : H/(p) c-Si heterojunction solar cells for various n-layer thicknesses. Cell area is 1 cm^2.

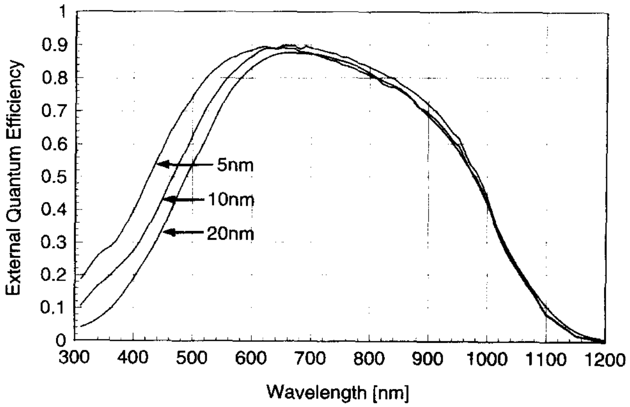

Fig. 3. Quantum efficiency as a function of n-layer thickness.

Table 2
Solar cell properties for cells with 1.83 eV band-gap films. Cell area is 1 cm^2

Time (s)	I_{sc} (mA)	V_{oc} (mV)	FF %	η (%)
150	28.5	597	63.6	10.8
100	29.3	599	64.9	11.4
50	29.8	598	66.9	11.9
25	30.0	596	72.4	12.9
15	29.8	590	73.1	12.9

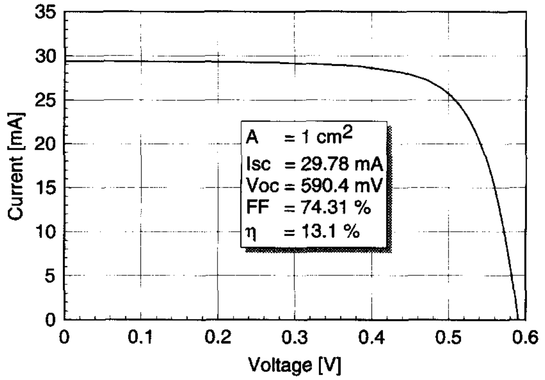

Fig. 4. Illuminated IV-characteristics of an (n) a-Si : H/(i) a-Si : H/(p) c-Si heterojunction cell, certified by ISE, Freiburg.

films compared to the low band-gap films. To obtain high fill factors these films again have to be very thin. But in this case the open circuit voltages drops down to values as found for the cells with the lower band-gap material. As a result there is no improvement of the efficiency by this concept.

It should be noted that in all cases the short circuit density is around 30 mA/cm^2. As can be seen by linear extrapolation from Fig. 2a that for a hypothetical layer with thickness 0 nm (that means no absorption) the current is limited to at least 31 mA. So for this types of cells with flat, polished surfaces the current is limited by the reflection losses and the transmission of the ITO layer. For an enhancement of the current one has to use textured substrates and/or a back surface field which will be done during further investigations.

3.2. (n) a-Si : H/(i) a-Si : H/(p) c-Si heterojunction

For an improvement of the solar cell efficiency an intrinsic buffer layer has been inserted between the substrate and the doped amorphous silicon layer. Fig. 4 shows the IV-curve of such a cell. The thickness of the intrinsic and doped layer was 5 nm. Due to the passivation effect of the i-layer the fill factor is further increased and the efficiency reaches a value of 13.1%. This value was certified by ISE Freiburg, Germany and included into the ISE PV-charts. It should be noted that in this cell structure the i-layer does not contribute to the optical absorption as can be seen from Fig. 5. The cell with an additional 5 nm thick i-layer has the same quantum efficiency as the cell with only a 5 nm thick n-layer although the total thickness is 10 nm. The reason is that for the cells of type 2 an electric field is present inside the i-layer which removes the photogenerated carriers so that they can contribute to the photocurrent.

3.3. Stability

The use of amorphous silicon layers in a solar cell structure always takes the risk that the cells exhibit light-induced degradation. Therefore we investigated the fate of an (n) a-Si : H/(p) c-Si solar cell with an initial efficiency of 12.5% under illumination. Fig. 6 shows that even after 60 h light soaking with 5 suns no degradation can be

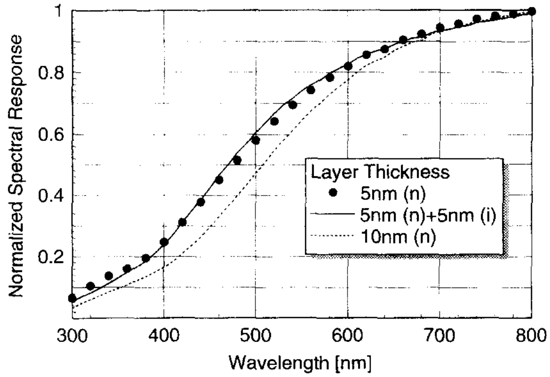

Fig. 5. Normalized spectral response for (n) a-Si : H/(p) c-Si heterojunction cells with 5 nm and 10 nm thick n-layers and an (n) a-Si : H/(i) a-Si : H/(p) c-Si heterojunction cell with 5 nm thick n- and i-layers.

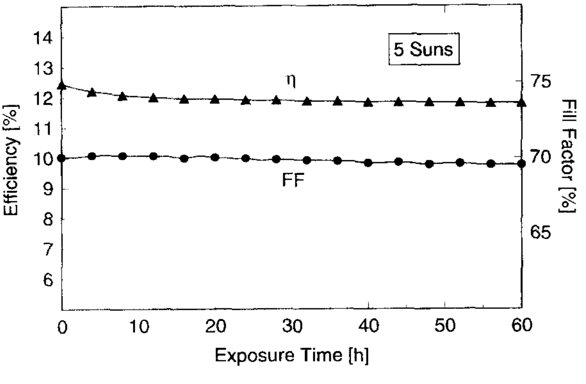

Fig. 6. Efficiency and fill factor as a function of exposure time of an (n) a-Si : H/(p) c-Si heterojunction cell under illumination with 5 suns.

observed. The efficiency and the fill factor remain nearly constant. The reason for this might be the fact that the used amorphous silicon layers are very thin and do not contribute to the photogeneration. The observed slight decrease was due to a constant heating up of the cell during the exposure time. Thus, it can be concluded that there are no restrictions for practical applications by light degradation.

4. Conclusions

(n) a-Si : H/(p) c-Si heterojunction solar cells have been successfully realized on cheap CZ material with efficiencies up to 13.1%. It is shown that the maximum current of this cells is not limited by the absorption of the amorphous n-layer but by the general cell design. A further improvement of the current is only possible by using textured substrates and/or a back surface field. A light-induced degradation is not observed.

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