ASYMMETRIC INTERMEDIATE REFLECTOR FOR N-I-P MULTI-JUNNCTION THIN FILM SILICON SOLAR CELLS

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ABSTRACT: We investigate n-i-p/n-i-p micromorph tandem cells deposited at process temperature below 200°C in order to be compatible with low Tg (<180°C) plastic substrates. In this configuration, the thick microcrystalline cell is grown first and tends to smoothen the initial substrate texture. Hence, the amorphous cell is grown on an almost flat surface that yields low current density. To prevent this effect and to obtain a proper current matching, an asymmetric intermediate reflector, creating a structure favourable for a-Si:H cell, is developed and incorporated into the cells. The effective optical thickness of the amorphous intrinsic layer can be increased by a factor of more than three. Hence, the light induced degradation is reduced below 10% for 180 nm amorphous layer whereas the degradation for cells without intermediate reflector is between 15-20%, because 300 nm amorphous top cell is required for matching. We present a-Si:H/a-Si:H micromorph tandem cells with 10.1 % stable efficiency after 1000h light soaking and triple junction a-Si:H/a-Si:H/μc-Si:H solar cell with initial efficiency of 10.4%.
Keywords: Intermediate reflector, tandem micromorph, flexible substrates

1 INTRODUCTION

The micromorph tandem cell [1] combines a top amorphous cell (a-Si:H) and a bottom microcrystalline cell (μc-Si:H). The coupling of light in these devices, to ensure a maximum device stable efficiency is complicated. Indeed, the light confinement of the long wavelengths (700-1100nm) should be optimal in the bottom cell without deteriorating its open circuit voltage (V_{OC}) and fill factor (FF) [2, 3], and the short circuit current (J_{SC}) should be well-balanced between the top and bottom cell while keeping the a-Si:H solar cell as thin as possible to limit the light induced degradation [4].

The standard design for high efficiency micromorph tandem solar cells in the superstrate configuration (p-i-n) is to use a textured front transparent conductive oxide (TCO) with a thin intermediate reflector (IR), with refractive index lower than silicon (typically $n_{IR} < 2$), added between the top and bottom cell to reflect part of the light in the top absorber as described by D. Dominé and P. Buehlmann [5, 6]. However, since the optimum morphology and feature size of the texture for the material growth and the light trapping are different for both the top and bottom cells, a trade-off has to be made for the optimised device. The standard design for substrate configuration (n-i-p) is to use a triple junction device [7] with SiGe sub-cells in order to minimize the thickness of the a-Si:H top cell and to achieve current matching. Nonetheless, the structures using SiGe require complicated profiling of the Ge content throughout the absorber layers [8].

Here, we propose a n-i-p/n-i-p micromorph tandem device structure with an asymmetric intermediate reflector (AIR), which has the potential to fulfill all the optical and the material growth requirements. Indeed, we can use a substrate structure that is well adapted for the μc-Si:H cell both for the silicon growth and the light trapping. Then, on top of the μc-Si:H cell we deposit an AIR with morphology and feature sizes close to the ideal for the a-Si:H top cell. Therefore, the substrate texture and the asymmetry of the AIR provide the ideal light in-coupling scheme for both top and bottom solar cells.

2 EXPERIMENTAL

The silicon layers are deposited by VHF-PECVD (70 MHz). The back contact, composed of hot silver substrate covered with thin ZnO (60 nm), is deposited by sputtering [9]. The top contact is ZnO deposited by low pressure chemical vapor depositions (LP-CVD ZnO) [10] which results in naturally textured film with a root mean square roughness of 70 nm for a 2 μm thick film. The efficiency of the solar cells is measured by J(V) measurement with AM 1.5g solar spectrum. The J_{SC} is determined by convolution of the external quantum efficiency (EQE) with the AM 1.5g spectrum and then the J(V) is normalized with the J_{sc_EQE}. This conservative method avoids uncertainties in the determination of the solar cell surface area.

3 RESULTS AND DISCUSSION

Our novel device scheme with an AIR is presented in Figure 1. The μc-Si:H is deposited on hot silver substrate which has morphology with large feature size (about 1 μm) needed for efficient light scattering for wavelengths between 750 nm and 1100 nm as shown by Sai et Kondo [11, 12]. The shape of the morphology has a moderate roughness in order to provide ideal conditions for the growth of µc-Si:H material [13]. The AIR is composed of 1.5 µm of LP-CVD ZnO deposited on top of the bottom cell. As shown in Figure 1, it results in the optimum feature size (about 300 nm) and morphology needed for the a-Si:H top cell [14]. Therefore, the blue-green light (500 nm - 750 nm) is scattered at the front of the top n-i-p cell, back reflected and most important back scattered at the AIR interface. The blue-green light is then trapped between the AIR and the top front contact in the a-Si:H top cell.

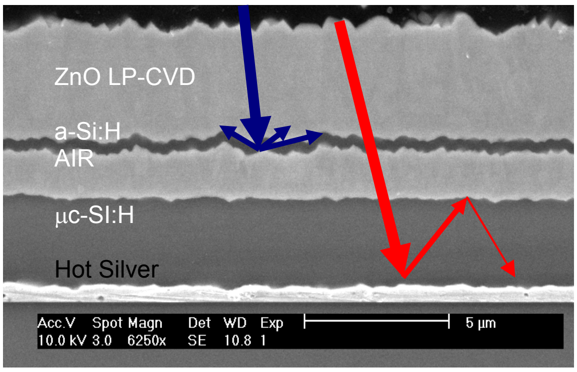

Figure 1: SEM micrograph of a nip/nip micromorph tandem cell cross-section with a AIR.

Figure 2 shows the EQE of our tandem devices with thin (< 1.5 µm) µc-Si:H cells. The initial and stabilized electrical parameters of micromorph cells without IR and with AIR are also compared in the Table I. It shows that with the AIR, the top cell can be made as thin as 140 nm and still generates 11.4 mA/cm^2. In tandem cells, the degradation is reduced to 8 % with the AIR compared to 18 % without IR but thicker 300 nm top cell.

Table I: Solar cell performance parameters (stabilized parameters are in parenthesis) of n-i-p micromorph tandem solar cells without IR (300 nm a-Si:H, 1.2 µm µc-Si:H) and with 1.5 µm thick LP-CVD ZnO AIR (140 nm a-Si:H, 1.4 µm µc-Si:H) deposited on glass covered hot silver.

Thickness [µm] a-Si/µc-Si	0.3/1.2 NO IR	0.14/1.4 AIR
V_{oc} [mV]	1.35 (1.34)	1.32 (1.34)
FF [%]	73 (62)	74 (70)
J_{top} [mA/cm^2]	10.7 (10.3)	11.4 (10.3)
J_{bot} [mA/cm^2]	11.5 (11.2)	10.6 (10.2)
Efficiency [%]	10.5 (8.6)	10.4 (9.6)
Deg. [%]	18	8

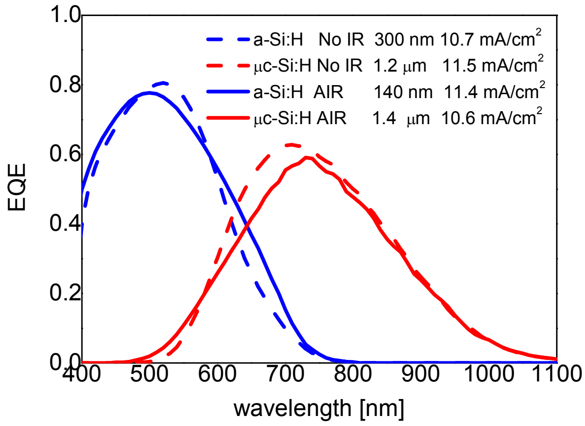

Figure 2: Initial EQE of nip/nip micromorph tandem solar cells without IR (300 nm a-Si:H, 1.2 µm µc-Si:H) and with AIR (140 nm a-Si:H, 1.4 µm µc-Si:H) deposited on glass plus hot silver.

In a next step we consider the case of optimised micromorph device with thicker bottom cell (3 µm). In this case the J_{SC} can be further increased in both cells while keeping the light induced degradation below 10%. Indeed, a micromorph n-i-p/n-i-p cell with 10.1 % stable efficiency has been realized (V_{OC}= 1.35V, FF = 65%, J = 11.5 mA/cm2) on glass substrate covered with hot silver as shown in Figure 3 and 4. If we replace the glass substrate covered with the hot silver contact by a fully flexible plastic substrate with 2D grating, we achieve a stable efficiency of 9.8 % (V_{oc} = 1.29 V, FF = 64%, J_{SC} = 11.9 mA/cm2) after 1000h of light soaking at V_{OC}, 50°C and 100mW/cm2 as reported elsewhere [15].

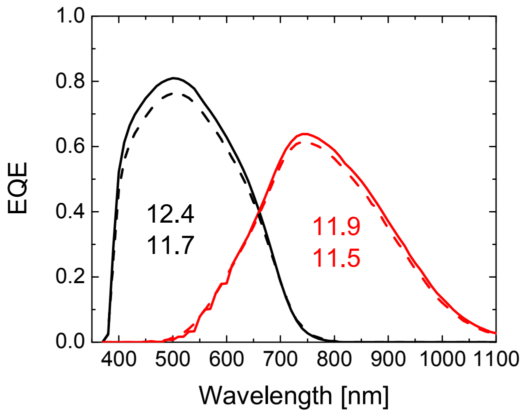

Figure 3: Initial and stabilized EQE curves of a tandem micromorph cell deposited on glass covered with a hot silver back contact.

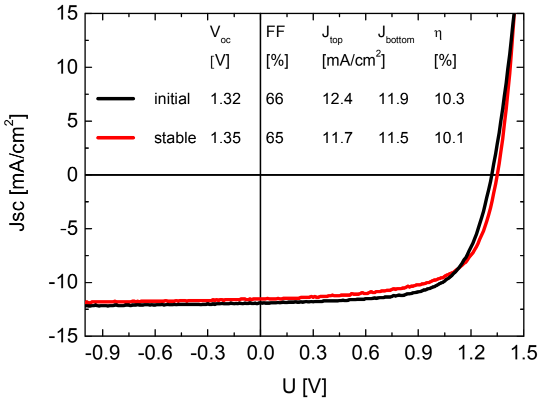

Figure 4: Initial and stabilized IV curves of a tandem micromorph cell deposited on glass covered with a hot silver back contact.

The AIR is also an efficient tool for triple junction structures with two purely amorphous top cells. A triple junction device with two a-Si:H cells does not offer further efficiency possibilities than a micromorph tandem cell since there is no increase of light absorption. Nonetheless, there are several advantages of making triple junction solar cells and modules. The voltage is higher than in micromorph cells. This limits resistive losses in the TCO, the light-induced degradation is reduced as it is the case for tandem a-Si:H cells compared to single junction a-Si:H cells. Since the J_{SC} potential is lower, a lower μc-Si:H thickness is sufficient. Therefore, for module and production costs, the triple junction solar cell is a promising concept. In Table II, we report on the initial efficiency of a tandem a-Si:H/a-Si:H and a triple junction a-Si:H/a-Si:H/LP-CVD ZnO/μc-Si:H solar cell with thicknesses of 60 nm, 300 nm, 1.5 μm, and 1.4 μm for the top, middle, AIR, and bottom cells, respectively. The back reflector is hot silver and glass covered with ZnO LP-CVD (as reported in [14]) for the triple junction and the tandem cell, respectively. The bottom cell EQE of the triple junction solar cell is not measurable. This happens with the AIR when the cell isolation is not ideal, i.e. there are shunts. From our experience [16], we expect a bottom cell J_{SC} between 8 to 9 mA/cm2, which will not be limiting. Therefore, the initial efficiency is 10.4% and is close to the best efficiency obtained with the micromorph in Table I.

In Figure 4, we compare the EQE of a-Si/a-Si tandem cell and the top and middle cell of the triple junction device. Both stacks are deposited on LP-CVD but the tandem has a back reflector whereas a μc-Si:H absorber is underneath the a-Si:H stack in the triple junction. The absorption difference in the amorphous absorber between the tandem stack with back reflector and the tandem stack with a microcrystalline absorber is equivalent to a current density 2.1 mA/cm2 as shown in Figure 5. As expected in the triple junction solar cell, the losses are mainly in the middle cell compared to the tandem structure. Indeed, the challenge in the triple junction solar cell with two amorphous cells is the J_{SC} of the middle cell. For that, our AIR is well adapted because it favors the J_{SC} in the amorphous absorber.

Table II: Initial performance parameters of a triple junction a-Si.H/a-Si:H/μc-Si:H and tandem junction a-Si.H/a-Si:H solar cell. In the triple junction, the μc-Si:H is 1.4 μm thick. The a-Si:H cells have a thickness of 60 and 300 for the top and bottom-middle cell, respectively.

	Tandem cell a-Si:H/a-Si:H	Triple a-Si:H/a-Si:H/μc-Si:H
V_{oc} [mV]	1.74	2.18
FF [%]	75	72
J_{top} [mA/cm^2]	6.7	6.6
$J_{bot\text{-}middle}$ [mA/cm^2]	6.8	6.7
Efficiency [%]	8.7	10.4

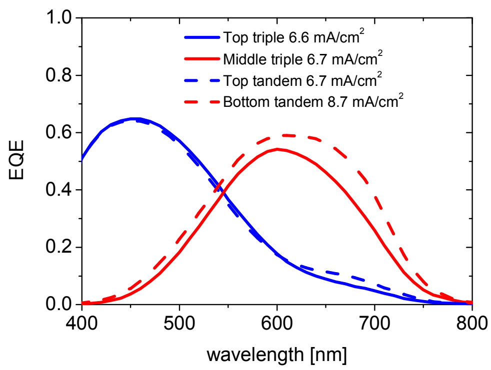

Figure 5: Initial EQE of a-Si:H/a-Si:H tandem and a-Si:H/a-Si:H/μc-Si:H triple junction solar cell.

4 CONCLUSION

The asymmetry of the AIR uncouples the light trapping scheme between the top and bottom cells in a tandem micromorph device. This increases the solar cell performance and offers a novel alternative to thin IR for tandem cells on glass substrates (p-i-n) and triple junction n-i-p solar cells on flexible substrates. In fact, the device on plastic foils has almost stable J_{sc} of 12 mA/cm^2 which is a first step toward stable efficiencies of 12 % (assuming V_{oc}=1.4 V, FF=71 %, and J_{sc}=12 mA/cm^2) in a micromorph cell on low T_g plastic substrates.

5 AKCNOLEDGEMENT

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