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DEVELOPMENT OF INVERTED MICROMORPH SOLAR CELLS

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ABSTRACT: This paper gives a comprehensive overview of the development of the amorphous silicon /microcrystalline silicon "Micromorph" tandem cell deposited in the inverted configuration (n-i-p/n-i-p). The objective of this work is to achieve a high stable efficiency (> 10 %) with an innovative cell structure, to be compatible with various types of substrates (including non-transparent or flexible substrates), while taking into account, at the same time, cost and ecological factors. In this context, ZnO conductive layers have been introduced as a replacement for ITO (Indium Tin Oxide) for both the top contact and the conducting back reflector. In a further important step towards potential cost reduction, high deposition rate of the bottom microcrystalline silicon cell has been thoroughly investigated. First results on complete structures show initial efficiencies up to 9.3 % on glass, aluminium and stainless steel substrates.
Keywords: Microcrystalline Si - 1; a-Si - 2; Multijunction Solar Cell - 3.

1. INTRODUCTION

Recent progress has demonstrated that microcrystalline hydrogenated silicon (µc-Si:H) is a very attractive material for the active layer of thin film solar cells. Efficiencies of up to 8.5 % have been achieved on entirely microcrystalline single p-i-n cells with no sign of light-induced degradation [1, 2]. By combining this cell with an amorphous silicon (a-Si:H)-based top cell and creating thereby a tandem structure (the so-called "micromorph" cell), efficiencies in excess of 11 % (10.7 % confirmed) have been achieved [3, 4]. These results have resulted in a renewed interest for thin film crystalline silicon cells (e.g. see [5, 6].

The "micromorph" structure has certain important assets when implementing high efficiency and low cost modules:

- High efficiency potential with the combination of a high gap top cell (a-Si:H) and a low gap bottom one (µc-Si:H),
- Same technology (PE-CVD) for both top and bottom cell deposition,
- Low temperature process,
- Improved stability (as compared to the a-Si:H/a-Si:H tandem) due to the resistance of µc-Si:H to light-induced degradation.

The inverted (n-i-p) configuration offers here some further additional advantages:

- Use of a variety of cheap substrates, including flexible and non-transparent ones (e.g. glass, stainless steel, aluminium sheets, plastic or metal foils),
- Wider range of temperatures for the deposition of the (a-Si:H) top cell; higher deposition temperatures are advantageous for obtaining optimised current matching of the top and bottom cells, and leads to better stability and higher current output (through a decrease of the optical band gap of the top cell).

With these assets, this inverted micromorph concept has advantages (for high efficiency and low cost solar cells) over the so-called STAR structure developed by Kaneka Corp [6, 7], the a-SiGe/a-Si tandem structure [8] or the triple-junction technology favoured by USSC [9].

The present work focuses on the development of micromorph cells deposited in the so-called inverted structure (substrate/n-i-p/n-i-p) within a project of the E.U., involving Neuchâtel and Jülich as the cell manufacturers. Besides optimisation of the top and bottom cells themselves, our joint investigations cover the development of ZnO/Ag textured back reflectors for an effective light trapping, and of ZnO top transparent conducting oxide (TCO) films. The choice of ZnO for the TCO was here motivated by environmental and cost considerations.

Due to the relatively low absorption coefficient of µc-Si:H, relatively thick i-layers are needed to absorb most of the light. As a consequence, the deposition rate of µc-Si:H is an important issue for the viability of this concept and has also been thoroughly investigated.

2. a-Si:H TOP CELL DEVELOPMENT

The top cell development focuses on three subjects: (1) The replacement of the commonly used ITO top contact by ZnO (this topic will be discussed in section 4.1); (2) the development of µc-p-layers which provide low optical absorption, as well as a low ohmic contact with the top ZnO layer and a high V_{oc}; (3) finally, the bandgap of the a-Si:H i-layers should be adjusted with respect to the requirements of the bottom cell.

2.1 Realisation of an optimised i/p/TCO interface

Major effort was dedicated to the development of optimised microcrystalline p-layers for the a-Si:H top cell. Details are given in a separate paper [10] and only the key results are summarised here: The comparison of different deposition techniques reveals that the VHF-technique (at a plasma excitation frequency of 110 MHz), in contrast to the classical RF-technique (at 13.56 MHz), provides microcrystalline growth of the p-layer on the underlying i-layer without the use of any interface treatment. Fill factors above 70 % have been achieved using the VHF-technique at 110 MHz. An optimisation of the doping ratio as well as of the hydrogen dilution ratio during p-layer growth results in a high open-circuit voltage V_{OC} of up to 880 mV, while using standard i-layer processes. However, most of the cells still suffer from a relatively low blue response, when compared with cells deposited in the regular p-i-n configuration; the origin of this loss can be attributed to absorption in the amorphous phase of the microcrystalline p-layer (see Ref. [10] for a more detailed discussion).

2.2 i-layer development

As compared to the regular p-i-n (superstrate) structure, the inverted n-i-p (substrate) structure offers a higher flexibility for the i-layer deposition parameters of the a-Si:H top cell. Depending on the requirements of the µc-Si:H bottom cell top cells containing either high bandgap a-Si:H i-layers leading to high V_{oc} (> 900 mV) or low bandgap i-layers which improve the current can be implemented. The latter type of i-layers has to be prepared at substrate temperatures significantly above 200 °C; such high temperature leads in the case of regular p-i-n cells to a loss in V_{oc}. This relationship between V_{oc} and i-layer deposition temperature is illustrated for both types of cells in Figure 1, confirming earlier work of Takahama et al. [11]. Due to deterioration in the TCO/p/i-interface region, the V_{oc} of regular p-i-n cells drastically decreases for substrate temperatures above 200 °C. On the other hand, the V_{oc} decrease of the inverted n-i-p cells simply corresponds to the observed decrease in bandgap of the i-layer with increasing substrate temperature.

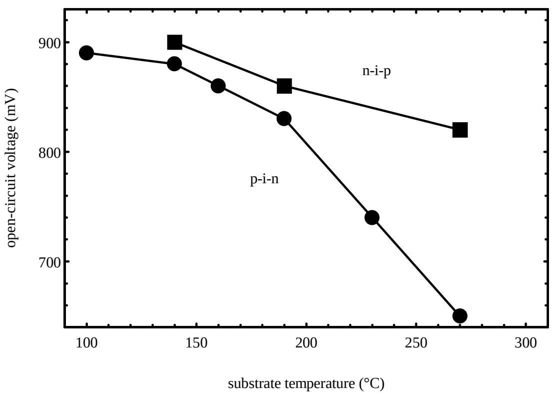

Figure 1: V_{oc} as function of the i-layer deposition temperature for p-i-n and n-i-p a-Si:H solar cells.

3. µc-Si:H BOTTOM CELL DEVELOPMENT

The objectives for the bottom cell are threefold: the deposition of the bottom cell must be optimised in terms of efficiency, V_{oc} and reduction of the deposition time. To obtain high micromorph cell efficiencies, it is quite clear that an increase in µc-Si:H bottom cell efficiency is desirable. The requirement of a high V_{oc} is given by current matching consideration with respect to the top cell; in order to reach the best top cell (and as a consequence of the micromorph tandem) stable efficiency, one has to limit the thickness of the top cell and therefore must keep a relatively low current throughout the device. Finally, due to the low absorption coefficient of the µc-Si:H material, one has to grow (at a limited and rather low value of deposition rate) relatively thick µc-Si:H i-layers. In this context, both an increase in the deposition rate and the implementation of an effective light trapping schema (see section 4.2) is of paramount importance in reducing deposition time to economically acceptable levels.

For this work, entirely µc-Si:H cells were deposited by the VHF technique on Asahi (type U) or Ag/ZnO-coated glass substrates. In order to get high deposition rates, i-layers were deposited using the VHF technique at 130 MHz; preparation details may be found in Ref. [12, 13]. Single µc-Si:H cell were terminated with ITO top contacts.

Cells with stable efficiencies in excess of 6 % have already been achieved on Asahi substrates [14]. In Figure 2, the spectral response and detailed performance of a 6.5 % cell is shown. Note that this cell exhibits also a very good saturation of the current (even at 0 V applied voltage). On the same type of substrate, an efficiency of 5.2 % at a deposition rate of 10.9 Å/s was also obtained [13, 14].

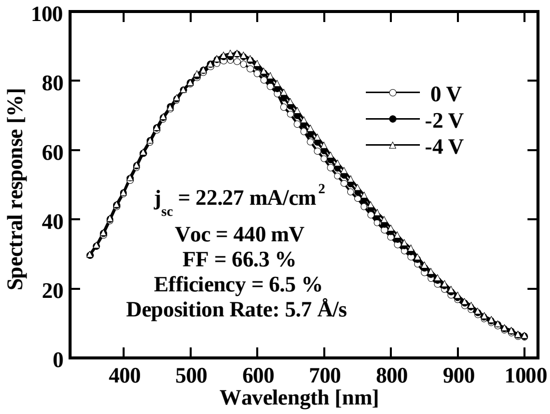

Figure 2: Spectral response and performances of an 3.6 µm thick n-i-p µc-Si:H cell deposited on Asahi (type U) at a deposition rate of 5.7 Å/s.

In order to further reduce the deposition time, we aim at reducing the cell thickness with the implementation of an efficient back reflector. Several cells were deposited on either flat or textured Ag/ZnO coated glass (see section 4.2). As one can see in Fig. 3, similar performances (as compared to Asahi U) were obtained on a flat (non-textured) Ag/ZnO-coated glass substrate with only half the i-layer thickness. A further gain is expected with the implementation of textured back reflectors (see section 4.2). No optimised µc-Si:H cells have been deposited so

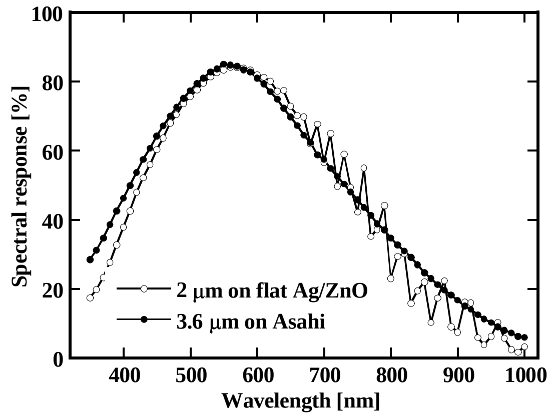

Fig. 3: Spectral response of an 3.6 µm thick inverted n-i-p µc-Si:H cell deposited on an Asahi (type U) substrate compared with the spectral response of a 2 µm thick inverted n-i-p cell deposited on flat Ag/ZnO-coated glass. Deposition rates were 5.7 Å/s and 5.5 Å/s, respectively.

far on textured back reflectors.

As far as the V_{oc} is concerned, the inverted n-i-p cells deposited so far exhibit values around 450 mV. In the regular p-i-n configuration, careful optimisation of the p-layer allowed us to boost the V_{oc} to values over 500 mV [2]; this optimisation work has now to be pursued and transferred to the inverted n-i-p structure.

4. TCO DEVELOPMENT AND LIGHT TRAPPING

For silicon based inverted n-i-p thin film solar cells, highly conductive and transparent ITO films are commonly used for the front contact. The typical film thickness is around 80 nm providing an effective anti-reflective coating. Due to the low absorption coefficient of the microcrystalline silicon, the incident light has to be efficiently scattered in order to get absorbed within the device. This optical confinement is necessary in order to obtain a sufficient long wavelength (infrared light) spectral response. For this purpose, the light scattering can be brought externally, e.g. by the introduction of a textured back reflector or by increasing the natural surface roughness of the µc-Si:H cell.

In our approach, all TCO and metal films serving as transparent top contact or textured back reflector are prepared by sputtering, which is a commonly available and highly industrialised thin film deposition technique. Note that a large variety of cheap substrates (e.g. float glass or metal- and plastic foils) can be used since the applied deposition temperatures (for both TCO and metal layers) are below 250 °C.

As TCO material, ZnO was preferred because it combines several advantages besides its high transparency and conductivity: ZnO is an abundant, cheap and environmentally friendly material. In combination with metal films, it provides high reflectivity and offers a high resistivity against hydrogen plasmas, which is an important advantage for the preparation of the microcrystalline bottom cell. In case of Al substrates, it serves as an effective diffusion barrier [15 which avoid the contamination of the cell i-layer with metal atoms. Moreover, we have shown that sputtered, initially smooth, ZnO films with appropriate structural properties can be chemically textured by a post deposition etching treatment with diluted HCl. The resulting surface texture exhibits distinct scattering properties for visible and infrared light [16, 17]. For the inverted cell, we combine texture-etched ZnO with highly reflective metallic films to realise a back contact with high reflectivity and tuneable light scattering properties.

4.1 Transparent top contact

Low-resistive, transparent ZnO and ITO (for comparison) films were prepared by magnetron sputtering. Highly transparent films (T > 84 %) with resistivities down to $4 \cdot 10^{-4}\ \Omega$cm and $7 \cdot 10^{-4}\ \Omega$cm for ZnO and ITO, respectively, have been achieved on glass substrates at deposition temperatures below 200°C. Resistivities distinctly below $5 \cdot 10^{-4}\ \Omega$cm were achieved for both materials at somewhat higher deposition temperatures. Using adapted microcrystalline p-layers, we compared ITO and ZnO front contacts in inverted n-i-p solar cells. The thickness of both ITO and ZnO layers was varied between 40 and 250 nm to determine the optimum value; a sharp maximum in the efficiency is observed when the anti-reflection conditions are fulfilled (see Fig. 4). The FF and V_{oc} of these cells were typically around 70 % and 850 mV, respectively. Since these cells are developed for the use as top cells in tandem devices, transparent substrates have been used, which explains the relatively low absolute values of the efficiency. A further slight improvement in FF (up to 72 %) was achieved by a fine adjustment of the sputter parameters during the first nanometers of top TCO growth by using a soft plasma start. In conclusion, we succeeded in replacing the ITO top contact by sputtered ZnO films without any drawback in device performance.

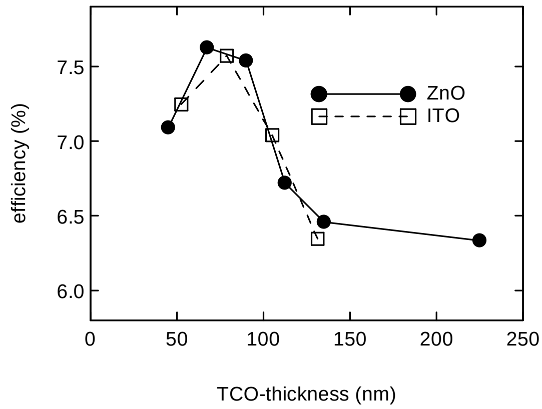

Fig. 4: Efficiency of amorphous inverted n-i-p cells with ITO or ZnO top contacts, as function of the TCO film thickness.

4.2 Textured Ag/ZnO back reflector

In addition to an increase of the deposition rate, the reduction of the thickness of the microcrystalline bottom cell is of great importance in the perspective of a future large-scale production. In order to keep the effective thickness constant, a light-trapping scheme with a textured back reflector has therefore to be implemented. Recently, Yamamoto et al. [7] reported a record efficiency of 9.3 % for a single n-i-p polycrystalline Si cell with a 1.5 µm thick i-layer, where both the natural surface roughness of the polycrystalline silicon and a textured back reflector were used for light-scattering. This result illustrates very well the potential of an efficient optical confinement.

For this back reflector, we investigate the use of metallic films (especially Ag) combined with chemically textured ZnO films. Since the electric properties for the application as textured back reflector are far less critical (than for the top contact), these ZnO films have been sputtered with a high amount of oxygen during the process (O_2/Ar=1 %), in order to avoid any loss due to free carrier optical absorption in the long wavelength range. We have already shown, that by simply varying the etching time it is possible to tune the diffuse reflection and improve the long wavelength response of amorphous silicon p-i-n cells [18]. However, in the case of the inverted micromorph structure, the surface texture has to be optimised according to the requirements of the microcrystalline bottom cells. For this purpose, a microcrystalline n-i-p test cell process (i-layer thickness: 1.5 µm) was used in order to characterise and optimise the light trapping properties of the textured Ag/ZnO back reflectors. Fig. 5 shows a remarkable reduction of the total reflection of µc-Si solar cells prepared on texture etched back reflectors as compared to the cells on the smooth (untextured) back reflector. The reduced reflection with increasing etching time indicates that a greater amount of the incident light is trapped inside the device. This is confirmed by I(V) measurements performed on these solar cells. Short-circuit current densities of 18.3 mA/cm^2, 19.4 mA/cm^2, and 20.5 mA/cm^2 have been achieved on the smooth, 7 s, and 30 s texture-etched substrates, respectively. Significant higher current densities is expected using optimised cell processes on these substrates.

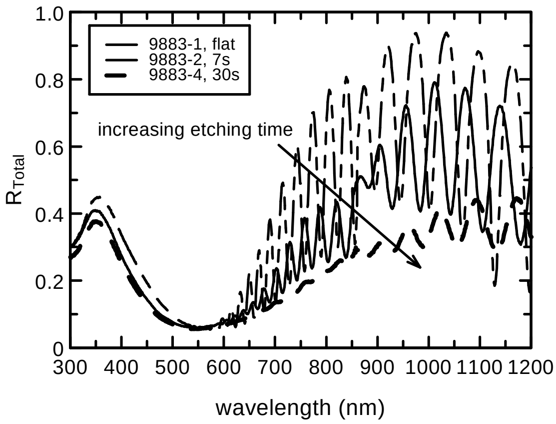

Fig. 5: Total reflection of µc-Si:H inverted n-i-p cells (with 1.5 µm i-layer thickness) co-deposited on flat, 7 s and 30 s etched glass/Ag/ZnO substrates.

3.3 Outlook

Our TCO development currently focuses on the development of highly conductive ZnO prepared by DC-sputtering from metallic Zn/Al targets. By avoiding the use of more expensive ceramics targets, this approach is consistent with our aim at minimal production cost and effectiveness of the micromorph concept in the frame of an industrial production.

4. FIRST COMPLETE TANDEM DEVICES

Complete micromorph tandem devices were realised on Al, stainless steel and glass substrates. Best efficiencies (initial) achieved so far are summarised in Table I. Efficiencies indicated here are preliminary results. So far, the full light-trapping scheme (i.e. the texturing of the back reflector) has not yet been incorporated. Still, the natural texture of the µc-Si:H surface already introduced some light scattering. However, this effect can be in future further strongly enhanced by the texturing of the back reflector, a step that should generally results in higher current and higher efficiency for the whole micromorph tandem.

Substrate	V_{oc} [mV]	I_{sc} [mA/cm^2]	FF [%]	η [%]
Al/ZnO (flat)	1240	11.1	67.3	9.25
SS/ZnO (flat)	1267	10.6	69.0	9.25
Glass/Ag/ZnO	1280	10.1	71.9	9.3

Table I: Performance of inverted (n-i-p/n-i-p) micromorph tandem cells deposited on various types of substrates. Efficiencies are given for the initial state (stable efficiency of the cell on aluminium substrate is 8.4 %).

As one can see in Fig. 6, from the spectral response of the cell deposited on Ag/ZnO, the current matching of this device is still far from perfect, which explained the rather high obtained FF value; a better current matching is expected from the introduction of the textured back reflector, which is going to increase the bottom cell current. The I(V) characteristics of this cell are plotted in Fig. 7.

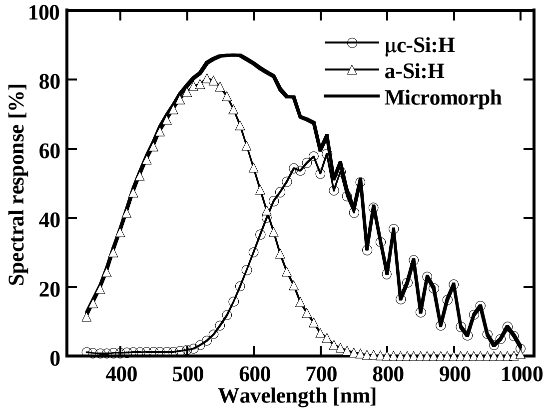

Fig. 6: Spectral response of an inverted micromorph cell deposited on a flat Ag/ZnO back reflector as well as the contributions from the component cells (the total micromorph current is here bottom cell limited). The I(V) characteristics of this cell may be found in Fig. 7.

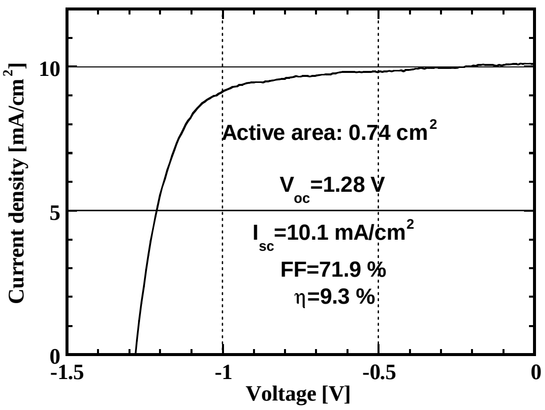

Fig. 7: I(V) characteristics of an inverted (n-i-p/n-i-p) micromorph cell deposited on a flat Ag/ZnO back reflector.

5. CONCLUSIONS

Inverted micromorph tandem concept offers an promising alternative for high efficiency, low cost, thin-film silicon solar cells. Compared to other technologies, the use of low temperature processes as well as the incorporation of only abundant and environmentally friendly materials is a further advantage of this technology.

In the regular p-i-n/p-i-n configuration, stable efficiencies in excess of 11 % have already been demonstrated. The inverted n-i-p/n-i-p configuration allows for a wider range of possible deposition conditions (especially for higher deposition temperatures) as well as for the use of wider range of substrates too; thus, this configuration has certainly a potential for even higher stable efficiencies and for lower module costs. In first complete devices as implemented on various types of substrates, initial efficiencies higher than 9.2 % have been obtained. A further implementation of already developed light-trapping schemes (texturing of the back reflector) as well as better current balancing between the top and the bottom cell, should results in a significant improvement of the efficiency.

As far as the stability of the micromorph tandem is concerned, the stability is only controlled by the top a-Si:H cell. Since the latter produce 2/3 of the total power of the micromorph tandem, it is critical to keep the top cell thickness as thin as possible. In this context, two different strategies may be followed. The first one, already partially studied, consist in an increase of the deposition temperature in order to reduce the bandgap and to obtain higher current. As an alternative, one can also implement an intermediate optical reflector (between the top and bottom cell) as a mean to increase the effective thickness of the top cell, as demonstrated by Pellaton Vaucher et al. [19].

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