Section 12. Solar cells

Basic efficiency limits, recent experimental results and novel light-trapping schemes in a-Si:H, µc-Si:H and 'micromorph tandem' solar cells

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Abstract

Theoretical: Limits for J_{sc}, V_{oc}, FF and efficiency of single-junction solar cells and tandems are derived, as a function of E_g, showing that: (1) double-junction 'micromorph' solar cells constitute an optimum combination of bandgap values; (2) main future gain for thin-film silicon solar cells will be increasing J_{sc}, by light trapping. Spectral ranges where light trapping has to act are presented, separately for a:Si:H and µc-Si:H. *Experimental*: For glass-pin type cells, light trapping is obtained at the front end, by use of rough TCO layers. For plastic-nip type solar cells, light trapping is obtained by texturing of the back reflector, which acts as basic layer for further growth. Both random texturing and periodic gratings have been used, but results presented are limited to single-junction a-Si:H and µc-Si:H solar cells. So far, the highest J_{sc}-enhancement obtained is approximately 20%.
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1. Introduction

Thin-film silicon, i.e. amorphous silicon (a-Si:H) and microcrystalline silicon (µc-Si:H) solar cells and, especially 'micromorph' (a-Si:H/µc-Si:H) tandems constitute, at present, one of the most promising avenues for further cost-reduction of solar cells. However, their stabilized efficiencies remain relatively low, as compared to wafer-based crystalline silicon (c-Si) solar cells, and even when compared to other forms of thin-film silicon solar cells, based on CIGS and CdTe, where at least in the laboratory, much higher efficiencies have so far been obtained [1,2]. On the other hand, there is considerable industrial production experience available for thin-film

silicon, and further massive manufacturing cost reductions can be expected, thanks to the synergy with the active-matrix liquid crystal display field. The combination of amorphous silicon (a-Si:H) and microcrystalline silicon (µc-Si:H) to form the double-junction 'micromorph' solar cell is, from a physical point of view, one of the most interesting thin-film tandem combinations usable for converting the AM 1.5 solar spectrum into electricity. This will be demonstrated, with the help of *fundamental considerations*, based on the gap energies involved (1.75 and 1.1 eV, respectively), as well as on the resulting limiting values for J_{sc}, FF and V_{oc}. The 'semi-theoretical' maximum efficiencies for all three types of thin-film silicon solar cells: a-Si:H, µc-Si:H and 'micromorph' will be derived.

Thereby, it is confirmed that there remains most to be gained by increasing the value of J_{sc}, through light trapping. Light trapping has to be effective in a well-defined part of the AM 1.5 spectrum, a part that is quite

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different in the case of a-Si:H than in the case of μc-Si:H. The present paper will present experimental results obtained with light-trapping schemes, both in the case of glass-pin type solar cells and also for substrate-nip type solar cells, where the substrate can be either stainless steel or plastic.

2. Theoretical part

2.1. Theoretical efficiency limits for homojunction solar cells

The upper limit for the short circuit current density J_{sc} can be computed by taking the normalized AM 1.5 spectrum and assuming that all photons with $h\nu > E_g$ (where h is the Planck constant, $\nu = c/\lambda$ with c the speed of light and λ the wavelength, and E_g is the energy gap of the semiconductor material considered) are absorbed and converted into electron–hole pairs that can be collected at short-circuit conditions. This results in $J_{sc}(E_g)$ as given in Fig. 1.

Assuming that the $J(V)$ characteristic of the solar cell under illumination can be written, according to the standard diode equation, as $J = J_0[\exp(qV/kT) - 1] - J_L$ (with $J_L = J_{sc}$), where J_0 is the reverse saturation current density and has the following empirical minimum value according to Green [3]

$$J_0^{\text{Green}} = J_{00} \exp(-E_g/kT) \text{ with } J_{00} = 1.5 \times 10^5 \text{ [A/cm}^2]. \tag{1}$$

The limit value for V_{oc} can then simply be written as

$$qV_{oc} = E_g + kT \ln(J_L/J_{00}). \tag{2}$$

The corresponding function for $V_{oc}(E_g)$ is shown in Fig. 2.

Fig. 2. Semi-empirical upper limit for the open-circuit voltage V_{oc}, as a function of the energy gap E_g of the solar cell material, based on Eqs. (1) and (2), hereunder.

The fill factor FF is expressed by $\text{FF} = (J_M \cdot V_M)/(J_{sc} \cdot V_{oc})$, where J_M and V_M are the current density and the voltage, respectively, at the maximum power point. Taking the diode equation and maximizing the product $(J \cdot V)$ by differentiation yields the following equation:

$$J_L/J_0 \approx (qV_M/kT) \exp(qV_M/kT). \tag{3}$$

Using the expressions for J_0, as well as the above equation, one finds the curve for $\text{FF}(E_g)$ as given in Fig. 3.

Finally, the limit efficiency of the whole solar cell can be computed by multiplying $J_{sc} \cdot V_{oc} \cdot \text{FF}$ and by divid-
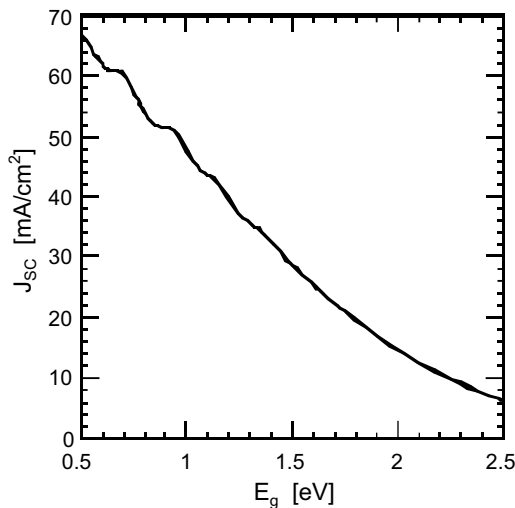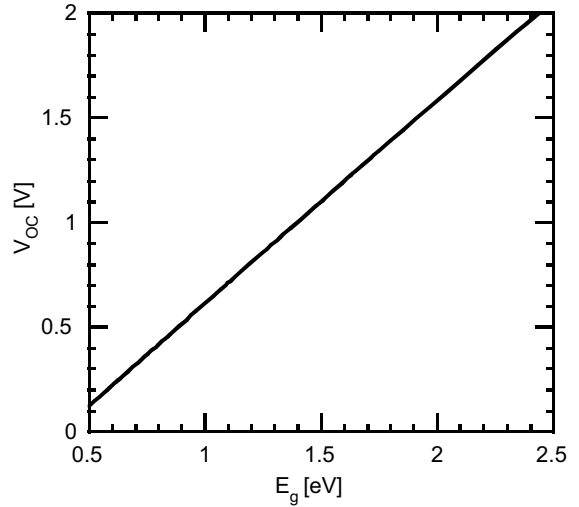

Fig. 1. Upper limit of the short-circuit current density J_{sc} as a function of the energy gap E_g of the solar cell material, under AM 1.5 illumination.
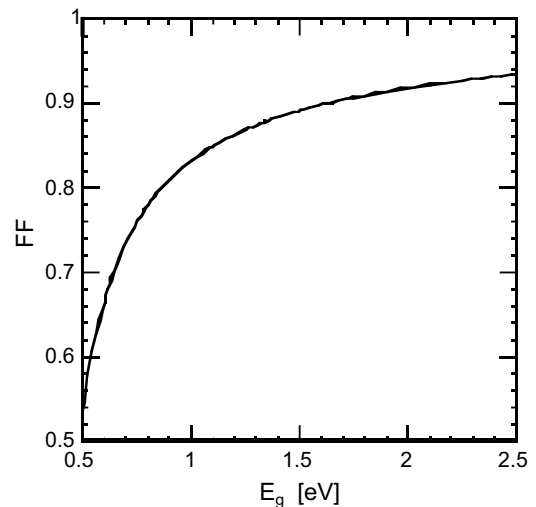

Fig. 3. Upper limit for the fill factor FF as a function of the energy gap E_g of the solar cell material based on an empirical minimum value (according to Green) for the reverse saturation current of the diode (Eq. (1)) and on above Eq. (3).
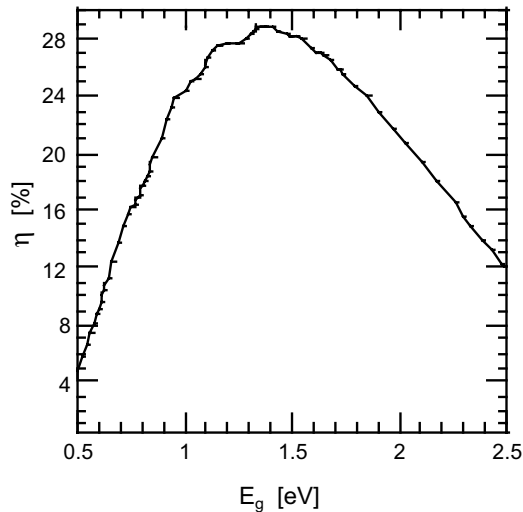
Fig. 4. Semi-empirical upper limit of the efficiency η as a function of the energy gap E_g of the solar cell material.

ing by the incident light energy. This yields the curve $\eta(E_g)$ of Fig. 4.

2.2. Comparison with experimental results generally obtained

Comparing the semi-empirical limits, from Fig. 2, for $E_g = 1.7–1.8$ eV, with actual values obtained during the last two decades for *amorphous silicon* (*a-Si:H*) solar cells, one notes that there remains in principle still a lot to be gained for V_{oc}. So far, however, in spite of many attempts, no V_{oc}-values higher than about 1 V were obtained for a-Si:H cells, and most practically usable cells have V_{oc}-values which are just around 0.85–0.9 V. There must be, therefore, some basic limitation on the V_{oc}-values of *amorphous* solar cells. The FF-value, on the other hand is linked to V_{oc}, it is also reduced in the degraded state, for a-Si:H solar cells, by the increase in dangling bonds and the corresponding increase in recombination losses. One therefore cannot expect here very high FF-values. As regards J_{sc}, relatively high values are already obtained, but this is due to the relatively high absorption coefficient resulting from the amorphous structure of the material, it is also only obtained thanks to the intensive light-trapping schemes already used for a-Si:H.

Comparing, on the other hand, the semi-empirical limits for $E_g = 1.1$ eV with the actual values so far reached for microcrystalline silicon (μc-Si:H) solar cells, one obtains the situation shown in Table 1.

The actual limits for V_{oc} and FF are in reality a bit lower, because thin-film silicon solar cells are generally required to have a p–i–n configuration and are not simply p–n diodes [4]. To date there exists, however, very unfortunately, no suitable closed-form, analytical theory for p–i–n diodes.

Table 1
Comparison between experimentally reached values and theoretical limits for J_{sc}, V_{oc} and FF of single-junction μc-Si:H solar cells

	Reached	Limit (Green)
J_{sc} (mA/cm^2)	20–30	44
V_{oc} (mV)	550–600	720
FF (%)	77	85

The largest scope for further improvement is clearly, for *all thin-film silicon solar cells*, given by J_{sc}. If one wants, however, to keep cell thickness reasonably low, this can only be done by optical means, i.e. by *light trapping*. This is a complex optical problem: it requires *suitably* textured (i.e. rough) layers and *very low optical absorption* in all transparent layers.

2.3. Theoretical efficiency limits for tandem solar cells

If the above considerations are extended to tandem solar cells, and one adds the condition of current continuity between top and bottom cell, one obtains the limit efficiencies represented in Fig. 5 for the case of semi-empirical considerations based on Eq. (1) as given by Green.

Even a quick glance at Fig. 5 suffices to see that the 'micromorph' tandem solar cell possesses truly an optimal combination of band gaps for a tandem solar cell, provided optical absorption and photogeneration/photocollection can be brought close to the limit values defined by the band gap. The only way to do so, without using excessively thick layers (that would result in additional recombination losses *and* in economically unacceptable production times), is by perfecting light-trapping techniques.
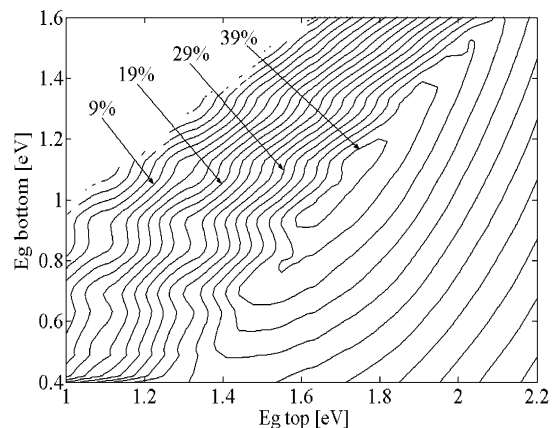

Fig. 5. Semi-empirical upper limit of the efficiency η as a function of the energy gap E_g of the bottom and top cells of a tandem solar cell based on an empirical minimum value (according to Green) for the reverse saturation current of the diode.
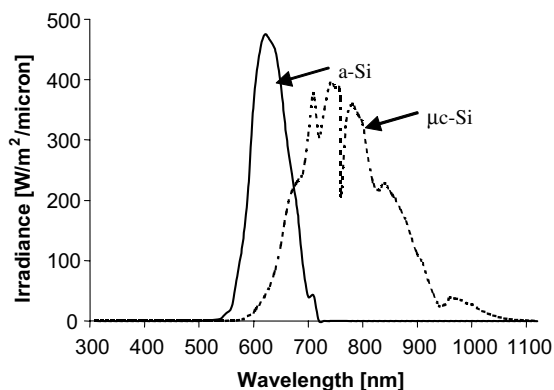
Fig. 6. Additional absorption due to an increase of optical path by a factor $m = 5$ (with a textured back reflector) as compared to the case of a flat, mirror-like back reflector, for an a-Si:H and a μc-Si:H single-junction solar cell, where the optical path through the cell is simply doubled ($m = 2$).

2.4. Spectral representation of light trapping

It is indeed instructive to examine the AM 1.5 spectrum and to put it in relation with known, standard absorption coefficient curves for a-Si:H (300 nm) and μc-Si:H (2 μm) layers, as corresponding to typical i-layer thickness d_i of pin- and nip-solar cells. Fig. 6 shows what can be gained in the solar spectrum for single-junction a-Si:H and μc-Si:H solar cells, if the average optical path is increased from just $2 \times d_i$ (as is obtained with an ideal, mirror-like, flat back reflector and no light scattering) to $5 \times d_i$ (as is generally easily obtained by light scattering, either through rough TCO, in the case of glass-pin cells, or through a textured back reflector, in the case of substrate-nip solar cells).

3. Experimental results

3.1. Glass-pin solar cells

3.1.1. Use of LP-CVD ZnO for light scattering

In glass-pin type solar cells, light trapping has so far always been obtained by the use of front-end transparent conductive oxides (TCO's) with high surface roughness and, thus, with high light scattering properties. One of the most efficient TCOs so far is ZnO obtained by low-pressure chemical vapor deposition (LP-CVD), as described in detail in [5–7]. Fig. 7 shows the SEM-image of LP-CVD ZnO layers produced at IMT Neuchâtel, as compared to those of commercially available SnO_2-layers (Asahi U-type). Fig. 8 indicates the reflection of the glass/TCO/solar cell system, for an a-Si:H solar cell, for these two different kinds of TCO. The reduced reflectivity obtained in the case of our ZnO layers can be clearly noted. It is evident that such a reduced reflectivity contributes to enhance the solar cell
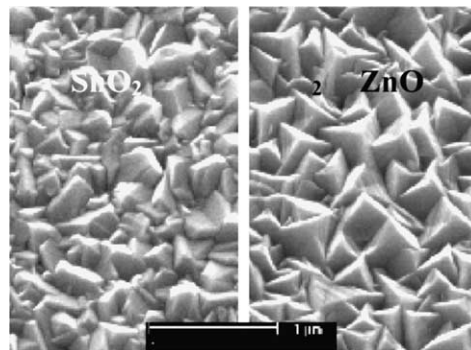

Fig. 7. SEM micrographs of rough surfaces of SnO_2 and ZnO layers.
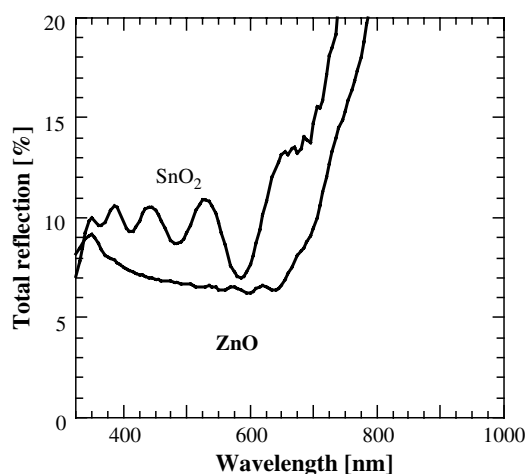

Fig. 8. Total reflection curves of glass/TCO/cell system, using either SnO_2 or ZnO as TCO layer.

efficiency, apart from the fact that the rough ZnO also increases light scattering. With this novel type of rough ZnO, developed at IMT Neuchâtel, a current increase of about 10% is obtained for both a-Si:H and micromorph solar cells, as compared with Asahi U-type layers. Note that the Asahi Company itself is in the process of developing improved SnO_2-layers, with better light-scattering properties.

3.1.2. Use of an intermediate reflector within 'micromorph' tandems

For 'micromorph' tandems, current balancing between the amorphous top cell and the microcrystalline bottom cell is an important issue. Because the amorphous top cell has (1) to be kept extremely thin, so as to avoid excessive light-induced degradation (2) is not situated directly next to the back reflector, it is usually the amorphous top cell that limits the current. In order to improve this situation, the use of an intermediate reflective layer between a-Si:H top cell and μc-Si:H bottom cell had been proposed as early as 1998 by IMT Neuchâtel [8]. This idea was recently taken up by a Japanese Industrial laboratory, leading to 'micromorph'

tandems (or 'hybrid' tandems, as they are called in Japan) with over 14% *initial* efficiency [9]. IMT Neuchâtel recently published results showing a *fully stable* 'micromorph' tandem cell with 10.7% stable efficiency that does not vary at all under light soaking [7]. Although this type of structure is very interesting from a conceptual point of view, it remains to be seen whether it is really economically feasible, because of three reasons: (a) the intermediate reflector certainly induces additional production costs (even if it can, later, be made of some form of silicon, deposited in the same PECVD reactor, as the other silicon layers of the whole tandem); (b) one is economically interested to work with µc-Si:H bottom cells that are as thin as possible; (c) from the point of view of temperature coefficient, a current limiting by the a-Si:H top cell may well be of advantage.

Vaneček et al. [10] have estimated the efficiency that can be obtained, *if* the front-end TCO and the cell's doped layers are further improved (by increasing the mobility in the ZnO, by reducing optical absorption by a factor of 3, and by reducing the defect absorption in the doped layers by a factor of 2), and *if* an optimized intermediate reflector layer is used. They find stabilized efficiencies of over 15%.

3.2. Substrate-nip solar cells

For this type of solar cell it is advantageous to obtain light trapping by structuring the back reflector. Because the back reflector is not at all exposed to the short-wavelength region of the solar spectrum (UV and blue light; this part of the spectrum is absorbed by the solar cell before it reaches the back reflector) and because the back reflector has only to reflect the light and not to transmit it (a task that can be much easier reconciled with the role of a conductive electrode for the solar cell), there is indeed more design flexibility for implementing improved light-scattering schemes in this configuration.

3.2.1. Randomly textured back reflectors on PET (a-Si:H cells)

Randomly textured back reflectors with different nano-structural dimensions have been fabricated on PET (by exposing PET substrates to O_2 and Ar plasmas [11]) and have been tested in a-Si:H cells. The AFM image and profile of one of the back reflectors resulting in the so far best solar cell performances are presented in Fig. 9.

Etching is 2 min in O_2 and then sputtered Ag and ZnO:Al layers are deposited. The most represented period and height are 620 and 80 nm, respectively. The RMS roughness is 48 nm. The large conglomerates are assumed as not to be taking part in the light-trapping process.

This back reflector has been incorporated in 250 nm thick a-Si:H solar cells. Spectral response measurements
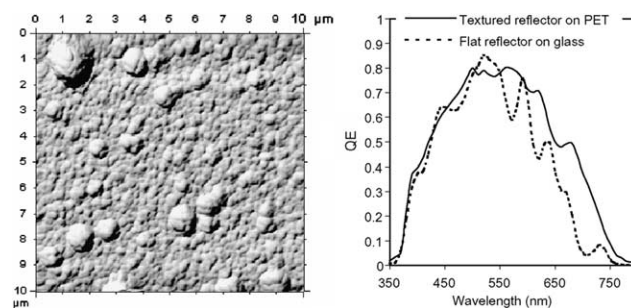

Fig. 9. AFM image of a performing randomly textured back reflector deposited on PET fabricated by O_2-plasma; spectral response curve in the degraded state of a nip-type a-Si:H cell deposited thereon, as compared to an identical cell on a flat mirror-like back reflector on glass.

were realized at the initial and degraded states and are shown in Fig. 9 for the degraded state. An evaluation of the results is presented in [11]. A current gain of 20% as compared to an identical cell deposited on a flat, mirror-like back reflector was obtained.

3.2.2. Randomly textured back reflectors on glass (µc-Si:H cells)

µc-Si:H solar cells have so far not been experimented on PET. Due to their longer deposition process, the maximum deposition temperature usable on PET for this kind of cells is certainly lower than that for amorphous solar cells and must still be evaluated. However, in order to determine the roughness adapted to enhance the light trapping of wavelengths between 600 and 1000 nm in 2 µm thick µc-Si:H cells, experiments have been performed on randomly textured back reflectors consisting of conventional, sputtered ZnO layers and of Ag-layers deposited by sputtering at temperatures between 200 and 400 °C on glass. Changing the deposition temperature during the sputtering process can easily vary the size of the nano-structures. Details are given in [11]. The most-performing back reflector has been deposited at 400 °C [12] and its texture characteristics have been determined by AFM (Fig. 10).

Single-junction µc-Si:H nip solar cells have been deposited on this textured back reflector yielding a current gain of 15% as compared to a co-deposited, identical solar cell on a flat back reflector; for the best cell, a J_{sc} of 24 mA/cm^2 (see also the spectral response in Fig. 10) and a stable efficiency of 9.2% have been measured [11,12].

3.2.3. Periodic gratings (a-Si:H cells)

A large number of numerical grating simulations and, also, of experimental trials, both with glass and with plastic substrates, containing periodic gratings and acting as back reflectors in nip-type a-Si:H solar cells, were carried out. Preliminary results and specific problems are described in [11,12]. Since those publications, further
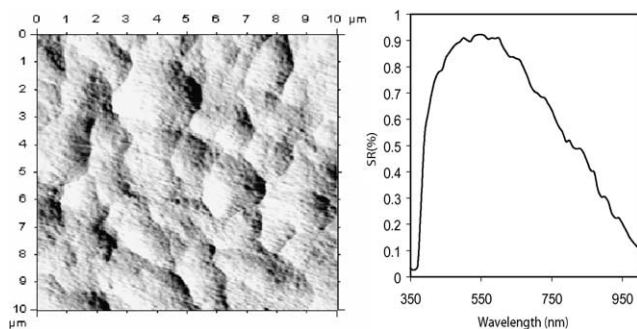
Fig. 10. AFM image of a performing randomly textured back reflector deposited on glass fabricated by sputtering of Ag and ZnO: Al layers at 400 °C; spectral response curve of a nip-type μc-Si:H cell deposited thereon.
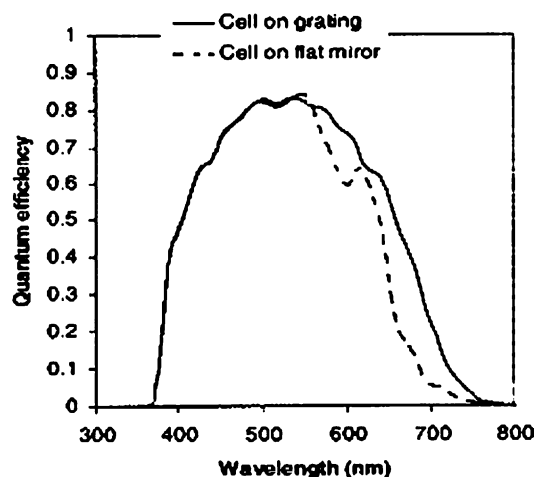

Fig. 11. Spectral response curve of an a-Si:H cell deposited on a periodic grating, as compared to an identical cell deposited on a flat mirror-like back reflector (initial state).

trials have been performed, while varying grating height, period, shape and material. Recently, a highly efficient grating design was found. Corresponding QE/spectral response results are presented in Fig. 11. A surprisingly high-current gain of 15% as compared to a co-deposited, identical solar cell on a flat reflector was found.

4. Conclusions

Theoretical considerations show that amorphous silicon and microcrystalline silicon form a band gap combination that is very near to the 'ideal' combination for tandem solar cells. Theoretical upper limits for conversion efficiencies of such cells are over 30%. However, silicon being a material with an 'indirect' band gap, useful absorption and photogeneration are up to now, very much lower in thin-film silicon solar cells than what they could be in the 'ideal case', as defined by the

band gap value alone. This is valid for all thin-film silicon solar cells, but especially for microcrystalline silicon, where the photogeneration needs to be enhanced over a wide spectral range, i.e. between 600 and 1000 nm wavelength, by suitable light trapping. Note that this is also the range, where free carrier absorption takes place in semiconductor and TCO layers. Thus, the main performance enhancement that can still be expected here, in future years, is clearly related to light management schemes, i.e. to light scattering and to reduction of optical absorption losses.

Thereby, relative gains in current and, consequently also in efficiency, of 25% to perhaps 50% can still be expected, in the next decade. This is, however a complex optical problem and poses difficult technological problems – problems that are quite different for glass 'superstrate' (glass-pin) type cells and for substrate-nip type cells. In the first case one is now mainly working on further improving the light scattering and optical absorption properties of the 'front-end' TCO. Thereby, ZnO is one of the prime candidates presently being examined. In the second case it is advantageous to work, above all, on texturing of the back reflector: Whereas random texturing of both PET substrates and Ag layers already yields very interesting results, use of periodic gratings has recently shown a first success, with an experimentally evaluated, relative current enhancement of approximately 15% (for an a-Si:H cell), as compared to a flat mirror-like back reflector.

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