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Influence of coevaporation process on CIGS solar cells with reduced absorber thickness and current enhancement with periodically textured glass substrates

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This study shows the fabrication of CIGS solar cells with various absorber thicknesses synthesized with two different methods: the classical 3-stages coevaporation process and a 1-stage coevaporation process. Structural characteristics and photovoltaics properties as function of absorber thickness are described. 1-stage coevaporation process gives lower efficiencies for CIGS solar cells with nominal absorber thickness (~2000 nm) but performs similarly or even better when the absorber thickness is decreased down to 600 nm. Periodically textured glass substrates with different feature sizes have been fabricated and used to increase current in 1-stage coevaporated CIGS solar cells. A current improvement up to 4.1 mA cm⁻² (6% relative) has been obtained leading to an increase in efficiency up to 5% relative. A maximum increase has been found when texturation size is similar to CIGS absorber thickness.

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1. Introduction

Among thin film technologies, Cu(In,Ga)Se₂ (CIGS) solar cells show the best performances with certified power conversion efficiencies above 22.3% obtained by different groups [1,2]. However, limited indium resources in the earth crust as well as its use in other applications may cap the development of CIGS production capacities to 80 GWp/year in 2050 [3], far from attaining the terawatt challenge [4].

Decreasing the absorber thickness is the most straightforward solution to reduce indium consumption in CIGS solar cells. However, it implies a reduction of the solar spectrum absorption in the active layer, particularly at long wavelengths, and thus leads to a decreased short-circuit current (Jsc) of the device [5]. Different strategies of light management have been conducted so far to tackle this issue and increase light absorption in the solar cells. One can mention the improvement of back contact reflection with highly reflective gold back contact [6], the introduction of plasmonic Ag nanoparticles as back reflector [7] or the use of dielectric scattering pattern [8].

In order to make these solutions suitable at industrial scale, structures for light trapping must be transferrable at low cost on large surfaces. Decoupling the elaboration of light management structures from solar cells fabrication gives a good opportunity to achieve this goal because it does not affect the low cost process flow to fabricate solar cells [9]. Our approach consists in fabricating and using periodically textured glass substrates on which coevaporated CIGS solar cells have been deposited. Techniques used for textured substrates fabrication are compatible with large surfaces (>1 m²) and based on soda-lime glass (SLG) which is traditionally used in CIGS technology.

The first part of this study deals with the comparison of two coevaporation processes to produce CIGS solar cells with reduced absorber thickness while the second part describes the influence of substrate texturation on solar cells photovoltaic properties.

2. Experimental section

2.1. Design of the structure

The design of the structure used in the second part of this study is depicted in Fig. 1(a). It consists in a 1-mm soda-lime glass (SLG) substrates in which SiO₂ spherical particles have been buried. Different diameters of spheres (0.5 μm, 1.0 μm and 2.5 μm) have been used in order to obtain texturation at different scales (respectively named S-0.5, S-1.0 and S-2.5 in the manuscript). Height of the pattern is about 1/3 of the sphere diameter and period of the texturation can be approximated by the particle diameter. Aspect ratio (defined as pattern height on the period) is thus close to 1/3. A dense thin layer (50 nm) of SiO₂ is deposited before the Mo back electrode in order to prevent Na migration.
and other contaminants from the SLG/SiO₂ spheres substrate. First it allows to compare more easily these structures with reference ones (same structures without buried spheres), because the role of SiO₂ spheres as diffusion barrier for Na is unknown. And second, Na diffusion is known to promote formation of MoSe₂ at the Mo/CIGS interface [10]. In this study Mo is used as back reflector, thus MoSe₂ thickness has to be reduced as much as possible in order to avoid optical losses in this layer. Na (and K) are however known to improve CIGS solar cells performances and are necessary to achieve high efficiencies; post-deposition treatment [11] can be directly applied to improve this process but has not been here used for the sake of simplification.

A typical Mo/CIGS/CdS/ZnO/ZnO:Al solar cells is deposited on these substrates; all steps of fabrication are described thereafter. Three different thicknesses of the CIGS absorber layer (ThCIGS) have been used for this study. Exact thicknesses may vary from the targeted values of 2000, 1100 and 600 nm and have been measured with X-Ray Fluorescence (XRF).

### 2.2. Textured substrates fabrication

The fabrication of the textured glass substrates is based on the deposition of a monolayer of silica spheres on a SLG substrate followed by an annealing step to bury these spheres into the glass. An enhanced Langmuir-Blodgett technique oriented to very large planar or non-planar substrates (called Boostream) is used to deposit this monolayer of spheres as described in reference [12]. This method allows homogeneous deposition on large surface (> 1 m²) at low cost (CEA estimation for spheres deposition is 3 €/m²). The periodicity of the texturation is linked to the shape and dimension of particles as well as the deposition technique. During Langmuir-Blodgett process, spheres automatically arrange in a hexagonal close-packed lattice during transfer from solvent to substrate.

After spheres deposition, a short etching step in SF₆ + CH₃F + O₂ gaz at 6.6 Pa is used in order to remove organic residual solvents. Substrates and spheres are then annealed in a lamp furnace at 800 °C for 30 s (parameters are varied in the 20 °C/10 s range depending on the sphere size) under inert Ar atmosphere to obtain substrates with two-thirds buried spheres.

E-beam evaporation is then used in an Oerlikon UniveX chamber to deposit a 50 nm thick SiO₂ layer from SiO₂ pellets. This layer is in-situ densified by ion beam bombardment to improve its diffusion barrier property.

### 2.3. Solar cells fabrication

These textured substrates have been used to increase light absorption in CIGS solar cells (Mo/CIGS/CdS/ZnO/ZnO:Al), particularly for devices with thin absorber layers. All deposition steps are compatible with 5 × 5 cm² substrates. In order to become insensitive to reproducibility issues, all deposition steps (including SiO₂ evaporation and CdS deposition) have been made simultaneously on 2.5 × 5 cm² textured substrates and on 2.5 × 5 cm² reference flat substrates which consist in SiO₂ coated SLG without texturation. Results based on flat reference substrates are presented in Section 3.1 and a comparison with textured substrates is conducted in Section 3.2.

A 500 nm Mo back contact is DC-sputtered in an Alliance Concept equipment at room temperature. A low Ar pressure (0.13 Pa) is used in order to improve reflectivity of the back contact. Description of the coevaporation processes for the CIGS layer is precisely made in the next section. The solar cell is then completed with a 50 nm thick chemical bath deposited CdS buffer layer and a 50 nm/450 nm thick ZnO/ ZnO:Al bilayer RF-sputtered at room temperature in a MRC chamber. Ni/Al grids are then deposited to collect current and 9 cells of 0.5 × 1 cm² are manually scribed in each sample.

### 2.4. CIGS coevaporation

Two coevaporation routes have been tested for CIGS deposition in this study; both of them have been performed in an Alliance Concept EVA450 deposition chamber. The first one is a classical 3-stages deposition process [13] implying a composition (GGI = [Ga] / ([In] + [Ga]) and bandgap gradient in the depth of the absorber layer. This process is described in reference [14]. Another deposition scheme has been tested as well, which consists in coevaporating simultaneously at constant fluxes Cu, In, Ga and Se on Mo coated substrates at 550 °C. This process, called 1-stage process, is supposed to give lower efficiencies than the 3-stages process but presents other advantages: an easier control of the deposition thickness and a better assessment of the influence of absorber thickness on solar cells properties. Indeed, in the case of 3-stages process, composition gradient is not scalable with the absorber thickness. For a fixed global GGI in the absorber, varying the thickness will modify slopes of the composition gradient and/or GGI at the interfaces and notch (position of minimum bandgap). With 1-stage deposition process, elemental composition as function of depth is much flatter despite some atomic migration can occur during deposition, see Fig. 2) and influence of absorber thickness on photovoltaic properties become more straightforward. Additionally, is has been argued in reference [9] that 1-stage deposition process could decrease CIGS deposition cost by almost a factor 2.

For both deposition routes, three absorber thicknesses have been targeted (2000, 1100 and 600 nm; some relatively important shift to targeted thickness have been observed and exact thicknesses are
mentioned when necessary), and deposited simultaneously on textured and reference flat substrates. Table 1 summarizes the absorber thicknesses and GGI ratio of the 3 series of samples synthesized for this study measured by X-Ray Fluorescence (XRF). Each series comprises a textured substrate and reference flat substrate for which stoichiometry and thickness are exactly identical.

2.5. Characterization

Samples have been characterized by SEM between all steps of the fabrication process in a LEO 1530 Hitachi equipment. Atomic composition of the CIGS absorber layer has been measured by XRF in a Fischerscope X-ray equipment. A Spectra-Nova’s CT Series Solar Cell Tester is used to perform current-voltage (J-V) measurements under simulated AM1.5G spectrum (100 mW·cm⁻²). All J-V measurements (light and dark) are performed at 25 °C in a four-point probe configuration. External quantum efficiency (EQE) measurements are carried out in a ReRa Spequest setup. The in-depth atomic composition of absorber layers was quantified by glow discharge optical emission spectrometry (GDS) using a Horiba GD Profiler 2. Total reflection measurements of the solar cells have been measured in a Perkin Elmer UV/Vis/NIR lambda 950 spectrophotometer with a 150 mm integration sphere.

3. Results and discussion

3.1. 1-stage versus 3-stages deposition processes

3.1.1. Structural characterization

In all processes, a GGI ratio close to 0.30 has been targeted. At nominal thickness (~2000 nm), a GGI ratio of 0.28 ± 0.02 (Table 1) is obtained corresponding to a CIGS bandgap of 1.15 ± 0.01 eV [15]. For all samples, a systematic increase of the GGI ratio with decreasing absorber thickness has been measured. The origin of this variation (up to +0.07 corresponding to a maximum bandgap increase of 38 meV) is not perfectly clear. It can be either an artefact of XRF measurement since it has only been calibrated at nominal thickness or a real GGI increase.

The main characteristic of 3-stages coevaporated CIGS layers lies into a GGI double gradient in the depth of the absorber [13]. GGI ratio as function of depth for both deposition routes are depicted in Fig. 2(a) for ~2000 nm thick CIGS absorber. The GGI gradient is clearly visible for the 3-stages process while much flatter profile is obtained for the 1-stage process. These measurements have been performed on samples directly synthesized on Mo coated SLG (no SiO₂ diffusion barrier). Thus, amount of Na is supposed to be higher in the samples for GDS measurements and elemental gradients more pronounced than in the samples fabricated with a SiO₂ barrier [16].

SEM cross sections of the different CIGS solar cells deposited on reference substrates with SiO₂ diffusion barrier are depicted Fig. 2(b). Samples with nominal thickness (~2000 nm) are on the left and thin CIGS (~600 nm) are on the right. In the case of 3-stages coevaporation process, the CIGS layer is made of big grains (~1 μm) irrespective of its thickness. This result is consistent with literature: in the absence of Na, big grains are generally observed [16]. On the contrary, grain size is only slightly enhanced without Na in the case of 1-stage deposition process (comparison with samples deposited on substrates without diffusion barrier is not shown). Again, the grain size is not affected by the thickness of the absorber layer.

3.1.2. Photovoltaic properties

The power conversion efficiencies (PCE) of all the cells fabricated on reference substrates with 3-stages and 1-stage coevaporation processes as function of absorber thickness are depicted in Fig. 3. The list of the samples can be found in Table 1: for each deposition route (3-stages or 1-stage), 3 thicknesses (T_{CIGS} ~ 600 nm, ~1100 nm and ~2000 nm) have been used and 3 samples have been fabricated for each thickness. 9 solar cells have been measured on each samples. Mean values presented in the rest of the manuscript are calculated over the 9 cells.

The GGI ratio increase as function of decreasing absorber thickness can induce a CIGS bandgap variation up to +38 meV for each series of sample and may slightly modify the behavior of solar cells as function of absorber thickness usually reported [5]. The maximum impact on open-circuit voltage (V_{OC}) is 38 mV and on short-circuit current (J_{SC}) is 1.4 mA·cm⁻². However, as far as 1-stage and 3-stages processes are compared for a given thickness, the GGI ratio discrepancy is much lower and the potential effect of such a small variation is carefully discussed thereafter.

![Fig. 2. (a) GGI profiles as function of absorber depth for 3-stages and 1 stage processes measured by GDS on flat substrates. Gds and Mo interfaces as well as notch position are indicated for clarity. (b) SEM cross section of CIGS solar cells on reference flat substrates with a SiO₂ barrier.](image-url)
In the 3-stages case, the PCE of CIGS solar cells continuously decreases with absorber thickness. The best efficiencies (12.9% due to the absence of Na) are obtained for the 1800 nm thick samples while efficiencies in the range 5%-7.5% are obtained for solar cells with 550 nm thick absorbers. A different behavior is found for the 1-stage coevaporation process: efficiencies for the thinner samples are comparable or slightly better than in the case of 3-stages process. At intermediate thickness, both processes are still comparable but a saturation of PCE with absorber thickness is obtained at ~1100 nm. As a consequence, PCE for 1-stage process is notably lower for solar cells with nominal thicknesses (~2000 nm) than for 3-stages process. This behavior is attributed to a lower fill factor (FF) for the 1-stage process than for the 3-stages process (Fig. 3(a)). The lower FF at nominal thickness in the case of 1-stage coevaporation process is caused by a higher series resistance Rs. Indeed, a clear correlation is found between JSC–JEQE and light Rs for all deposition processes as depicted in the inset of Fig. 3(d). JSC is clearly limited by series resistance while this effect is not sensitive for EQE because of the lower amount of current generated during this measurement. It provides a further evidence that Rs is playing an important role in limiting PCE for 1-stage process at nominal thickness.

The lower JSC and FF of the 1-stage process is offset by a higher Voc for the intermediate and low thickness samples. This higher Voc (~60 mV) cannot be totally attributed to a variation in bandgap due to composition changes: GGI ratio given by XRF for the considered samples are roughly similar (Table 1) and can only explain a 15 mV difference. This is confirmed by EQE measurements. Fitting of dark J-V curves reveals that dark saturation current is slightly decreased with small increase in ideality factor for 1-stage process. Both reasons explain a higher Voc but further analysis to explain these differences have not been carried out.

These results confirm that the 3-stages process gives better efficiency for CIGS solar cells with nominal absorber thickness (ThCIGS ~2000 nm) principally because of a better FF due to lower series resistance. However, as far as ultrathin absorber are targeted (ThCIGS <500 nm), 1-stage deposition process are very promising since they exhibit comparable or better efficiencies at reduced deposition cost [9].

### 3.2. 1-stage coevaporated CIGS on textured substrates

All CIGS layers with different conditions (1-stage/3-stages for various ThCIGS) presented in the previous section on reference flat substrates have been deposited simultaneously on textured substrates. Textured substrates with sphere diameters of 0.5 μm (S-0.5), 1.0 μm (S-1.0) and 2.5 μm (S-2.5) have been used in Series 1, Series 2 and Series 3 respectively.

However, the low Rs obtained for thin samples synthesized with the 3-stages process is even more decreased by the use of textured substrates. Thus, a majority of these cells are short-circuited and results are not useable. As a consequence, and since 1-stage coevaporation process is more promising for CIGS solar cells with reduced absorber thickness,
Table 2
Comparison of the photovoltaic properties of the 1-stage coevaporated solar cells on flat reference substrates (left column) and on textured substrates (right column). For each substrate type (S-0.5, S-1.0 and S-2.5) and CIGS thickness, mean values on the 9 cells per sample are presented. Additionally, values for the best cell are given (in brackets) when necessary. Light Rs and RSh are extracted from J-V curves under AM1.5 spectrum.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>ThCIGS</th>
<th>Name</th>
<th>PCE (%)</th>
<th>FF (%)</th>
<th>VOC (mV)</th>
<th>JSC (mA·cm(^{-2}))</th>
<th>Light RS ((\Omega)·cm(^2))</th>
<th>Light RSh ((\Omega)·cm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-0.5</td>
<td>570</td>
<td>ThCIGS570/S-0.5</td>
<td>6.0(6.5)</td>
<td>4.4(6.6)</td>
<td>56(58)</td>
<td>44(56)</td>
<td>483(493)</td>
<td>392(506)</td>
</tr>
<tr>
<td>S-1.0</td>
<td>580</td>
<td>ThCIGS580/S-1.0</td>
<td>6.6(7.1)</td>
<td>2.7(6.0)</td>
<td>59(59)</td>
<td>33(53)</td>
<td>488(490)</td>
<td>360(512)</td>
</tr>
<tr>
<td>1130</td>
<td>ThCIGS1130/S-1.0</td>
<td>9.1</td>
<td>5.1</td>
<td>63</td>
<td>37</td>
<td>520</td>
<td>492</td>
<td>27.6</td>
</tr>
<tr>
<td>2040</td>
<td>ThCIGS2040/S-1.0</td>
<td>8.7</td>
<td>5.2</td>
<td>59</td>
<td>37</td>
<td>513</td>
<td>504</td>
<td>28.7</td>
</tr>
<tr>
<td>S-2.5</td>
<td>470</td>
<td>ThCIGS470/S-2.5</td>
<td>4.6</td>
<td>0.9</td>
<td>54</td>
<td>26</td>
<td>401</td>
<td>188</td>
</tr>
<tr>
<td>910</td>
<td>ThCIGS910/S-2.5</td>
<td>7.7</td>
<td>4.9</td>
<td>60</td>
<td>39</td>
<td>487</td>
<td>457</td>
<td>26.2</td>
</tr>
<tr>
<td>1640</td>
<td>ThCIGS1640/S-2.5</td>
<td>8.4</td>
<td>8.7</td>
<td>58</td>
<td>53</td>
<td>490</td>
<td>514</td>
<td>29.4</td>
</tr>
</tbody>
</table>

Fig. 4. (a) Jsc and (b) PCE of the 1-stage process CIGS solar cells fabricated on reference substrates (yellow) and textured substrates (blue) for different texturing sizes (S). Data points for textured samples have been a little bit x-translated for greater clarity. Comments in the Jsc graph are reference to the EQE measurements (Fig. 5). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
relative are obtained. In the other cases (ThCIGS1130/S-1.0 and ThCIGS910/S-2.5), the decrease of the FF dominates the current gain.

Indeed, solar cells on textured substrates suffer from a systematically lower FF than the solar cells on flat reference substrates (Table 2). This decrease is attributed to a higher Rs as well as a smaller Rsh. When the shunt resistance is too strongly impacted by the substrate texturation (Light Rs < 70 Ω·cm²), degradation of the Voc is equally observed. On the contrary, when light Rs have similar values for flat and textured substrates, Voc in the latter case can be very slightly improved due to a small increase in the diode ideality factor in the dark (measurement not shown).

The higher Rs in the case of textured substrates is attributed to an increase of the sheet resistance of the Mo and ZnO:Al supporting layers. Sheet resistance of the back electrode on flat reference substrate is 0.33 Ω·sq⁻¹ while values between 0.70 Ω·sq⁻¹ and 1.60 Ω·sq⁻¹ have been measured for S-0.5, S-1.0 and S-2.5. Texturation also implies an increased roughness for ZnO:Al deposition which leads to a higher sheet resistance in this layer [20].

Origin of Rs decrease has been tentatively explained with SEM cross-sections depicted in Fig. 6. First, it is obvious that the growth of Mo back contact is strongly affected by the size of texturation. For S-0.5, the SiO2 spheres lead to the formation of almost disjointed Mo pillar while a very conformal Mo deposition is obtained for S-2.5. Intermediate S-1.0 texturation reveals rather good conformity of Mo layer on SiO2 spheres with however smoothed texturation. As a consequence, CIGS deposition is very conformal for S-2.5 and the texturation provided by the glass substrate is translated to ZnO layer on top of the solar cell. It is not the case for S-0.5 texturation because grain size is not much smaller than texturation size and aspect ratio of the glass features is softened by the Mo growth.

Thus, for samples with important texturation transferred at the Mo/CIGS interface (i.e. large scale compared to CIGS grain size, namely S-1.0 and S-2.5), Rs strongly decrease when the absorber thickness is too low (i.e. comparable to grain size) because CIGS cannot accommodate the texturation of the substrate. This result is particularly highlighted in the ThCIGS910/S-2.5 case for which Rs is below 100 Ω·cm² on textured substrates. SEM pictures made on 3-stages coevaporated CIGS solar cells on textured substrates (not shown) confirm this assumption: as the size of grains obtained on reference flat substrates is not affected by texturation it is not possible to have a perfectly conformal CIGS layer with grain size similar or bigger than texturation features. Thus Rs decrease for 3-stages process is even more pronounced on textured substrates than for 1-stage process.
This technological problem of grain size versus texturization size can be partially solved by decreasing grain size with incorporating more Na into the absorber layer. Thus, post-deposition treatments are expected to improve the process at Voc level (decrease of recombination [11]) as well as FF (increase in Rs due to smaller grains).

From these SEM pictures, it can be mentioned as well that the disjoint pillar growth for S-0.5 texturation can explain the poor adherence of CIGS layers on these textured substrates.

4. Conclusion

In this study, we explored two routes for fabricating CIGS solar cells with decreased absorber layer thicknesses. Additionally to the classical 3-stages coevaporation route, we demonstrated that the 1-stage route with decreased absorber layer thicknesses. Additionally to the classical 3-stages coevaporation route, we demonstrated that the 1-stage coevaporation method can be chosen as far as solar cells with reduced absorber thicknesses are targeted. The lower efficiency at nominal thickness due to higher Rs is not observed for thinner samples and comparable or better performances are obtained for submicronic CIGS solar cells.

CIGS solar cells with thin absorber thickness suffer from low Jsc due to insufficient light absorption. We have used periodically textured glass substrates to improve light trapping into CIGS absorber layers and we have demonstrated that it allows to obtain current (up to 4.1 mA cm⁻², >6% relative) and efficiency (up to 5% relative) increase in our 1-stage coevaporated solar cells.

The process described in this study can be easily improved by incorporation of alkali post-deposition treatment in order to achieve higher efficiency. Further developments have to be carried out to notably increase reflectivity of the back contact in order to obtain more pronounced current gain. Finally, the proof of concept of using textured glass substrates for CIGS solar cells with reduced absorber thickness has been demonstrated.

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