3.1 Publishable summary

3.3.1 Project context and objectives

Solar cells based on single-crystal silicon or epitaxial compound semiconductors provide the highest conversion efficiency. However, single-crystal solar cells and associated concentrator cells are still higher in cost than desired for generalized commercial use. Thin-film solar cells provide a lower cost alternative to bulk and epitaxial single-crystalline solar cells. Several thin-film based solar cells do exist, including copper indium gallium diselenide $Cu(In,Ga)Se_2$ (CIGS), Cadmium Telluride CdTe, organic materials, amorphous silicon, microcrystalline silicon, and thin-film silicon alloys.

The minority carrier diffusion lengths are generally small in these polycrystalline or amorphous thin films, requiring thin layers to maximize charge collection efficiency. The requirement for thin layers for maximum charge collection efficiency, however, is contradictory to the requirement of maximizing solar energy absorption. Optical absorption in thin films is particularly small at longer wavelengths near the band edge of the thin-film material, where the absorption coefficient is low.

As a result, the optical design aimed at increasing solar cell's light-trapping capability is of prime importance. Randomly textured surfaces have been used and investigated for both bulk crystalline and thin-film solar cells for many years. These randomly textured surfaces are generally achieved through etching techniques and aim to provide total internal reflection in a thin-film structure. Lithographically defined one-dimensional (1-D) and 2-D periodic gratings have also been investigated as an alternative to randomly textured surfaces. Both random and periodic structures have merits and drawbacks. There is a strong need **to optimize the design of surface texture for the efficient use of the broad solar spectrum.**

According to these considerations and supported by modelling work, novel approaches have been developed showing that double textures (i.e. long range and short range interpenetrated textures of different statistical parameters) on new Transparent Conductive Oxides layers (SnO_2:F) provide improved scattering characteristics. Such double textures can also be obtained by patterning the glass substrate and texturing the TCO surface. The benefit of this "modulated surface texture" (MST) was demonstrated by a significant increase in External Quantum Efficiency provided by both antireflective and scattering properties. But, to become an industrial reality, this approach requires new process chains, because patterning of a glass substrate by the usual lithography technologies is not compatible with a low cost technology based on thin films. **AGATHA aims to develop a low cost process chain to introduce advanced optical trapping scheme based on MST in Si based and CIGS thin film solar cells.** This MST can be achieved both for superstrate (Si based solar cells) and substrate (CIGS based solar cells) configurations. This 3-steps process involves (Fig. 3.1.1)

1. **Hot embossing of an asymmetrical** periodic grating **in the glass substrate** for the long-range texture.
2. Deposition of the electrode on the structured glass (TCO layer for Si-based solar cells in superstrate configuration, Mo for CIGS solar cells in substrate configuration).
3. Achieving the texture modulation (additional short range texture)
   - **a.** By chemical etching for **TCO texturation** (Si-based solar cells)
   - **b.** By Mo nanoparticles (NPs) deposition for **Mo texturation** (CIGS-based solar cells)

The major technical objectives of the project have been reviewed and slightly modified during the mid-term meeting because photovoltaic industrial environment drastically changed since the initial starting date of the AGATHA project (2010). In order to match with the current industrial requirements, they can be described as:

- **For CIGS technology,** the goal is to decrease absorber thickness from 2.5 µm to 600 nm while keeping short circuit current (J_{sc}) and other photovoltaic parameters constant.
- **For Si-based technologies employed in a double junction structure (a-Si:H/µc-Si:H),** the goal is to improve efficiency while decreasing top cell (a-Si:H) absorber from 250 nm to 150 nm and keeping bottom cell (µc-Si:H) at the same thickness**.**

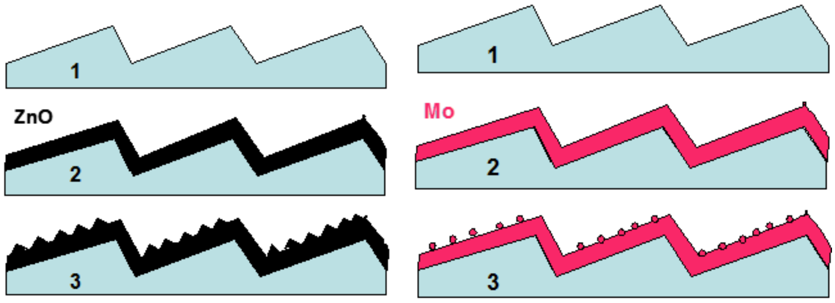

Figure 3.1.1: AGATHA concept of MST and process chain to achieve it for Si-based thin film solar cells (a) and CIGS-based solar cells (b)

Despite the modification of objectives, methods employed into the AGATHA project are still valid to meet the current industrial requirements.

- For Si-based technology, the main concern in 2016 is to drastically improve power conversion efficiencies in order to stay competitive with other technologies. At industrial level, thin film Si solar cells are only employed in multijunction devices with a current limited µc-Si:H bottom cell. Deposition throughput for this material has been improved and is no more the limiting factor. Using light trapping strategies to improve efficiencies of the bottom cell with the nominal thickness (1.6 µm) meets the industrial targets for this technology. At the same time, light trapping strategy can allow to decrease the thickness of the top cell (a-Si:H) in order to reduce the Stabler-Wronski effect and **to increase by 10% the stabilized efficiency of the top cell**.
- Concerning CIGS solar cells technology, the reduction of absorber thickness is still a main concern at industrial level in order to decrease In consumption and allow it to share a significant part of the photovoltaic market. Thus, the use of textured substrates is expected to permit a decrease by almost a factor 5 of the In consumption while keeping photovoltaic properties unchanged and particularly J_{SC}. This gain will go along with a decrease in the €/W indicator due to reduced deposition time (higher throughput) and lower material consumption.

3.3.2 Work performed by the European consortium during the AGATHA project

Efforts developed by the European consortium during the AGATHA project has been dedicated to the production of textured substrates and to the fabrication of solar cells and mini-modules of the different photovoltaic technologies on these substrates. Simulation tasks have been carried out to assess the benefit of new substrates on photovoltaic performances of solar cells.

- **Simulation activity**

Based on material properties obtained in the first period of the project from optical measurements carried out by the different partners, simulation activities have been used to describe the optical behaviour of solar cells and predict the influence of textured substrate. As the consortium has no experience in term of optical simulation for the CIGS technology, a particular attention has been paid to the definition of the model. A 3D optical modelling of the CIGS solar cell taking into account roughness of all layers has been developed and fits very well the experimental measurements has shown in Fig. 3.1.2 (a). For Si thin film technologies, models were already available at TUD.

As textured substrates finally used in the AGATHA project have been fabricated alternatively by the European consortium, the design of the features originally forecasted in the project was not achievable. Simulations conducted in the first part of the project were thus useless and new simulations have been conducted with the new substrates. A first step of substrate characterization and modelling has been necessary before simulation of solar cells can be performed.

Last, optical simulation of different photovoltaic technologies (CIGS and a-Si:H/μc-Si:H double junction) have been performed on their respectively available textured substrates. Valuable insights on light trapping properties as function of texturation parameters have been obtained.

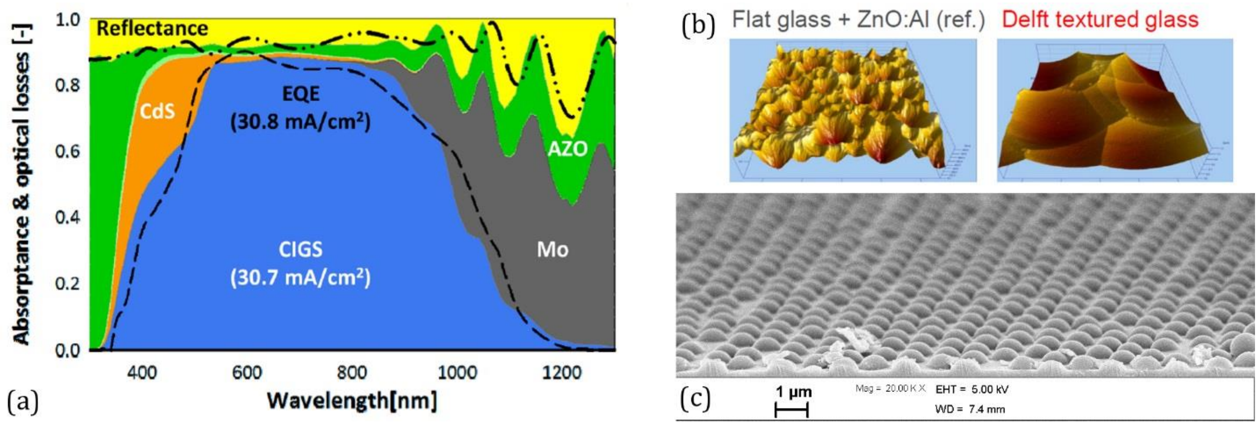

Figure 3.1.2: (a) 3-D optical modelling of a CIGS solar cells. Experimental EQE (black dashed line) is shown on the same graph. (b) AFM images of the Si technologies substrates: reference flat sample + etched TCO on the left and chemically etched glass on the right. (c) SEM image of a microspheres textured substrate for CIGS technology.

- **Substrates fabrication**

As no substrate has been received from the Indian consortium during the whole AGATHA project, European consortium decided to fabricate their own textured substrates. Two kinds of substrates have been employed. First, TUD developed randomly textured substrates obtained with chemical etching of sacrificial layer and transfer to glass of the features. On top of these substrates, a TCO layer is deposited and an additional etching step is performed to provide the small scale texturation. These substrates, used for Si-based technologies, are later called *chemically etched substrates* (Fig. 3.1.2 (b)) and are compared with reference substrates consisting in flat glass with etched TCO.

In parallel, CEA fabricated periodically textured substrates with the use of SiO_2 microspheres of different sizes buried into glass substrates and covered with Mo back electrode. No small scale texturation has been brought because it has been demonstrated by numerical simulation that it would not have a positive impact on photogenerated current. These substrates, called *microspheres textured substrates* (Fig. 3.1.2 (c)) have been used for the CIGS technology and are compared with Mo coated flat reference glass.

- **Solar cells implementation**

Solar cells and mini-modules with ultrathin absorber layers have been deposited on these new substrates. Concerning Si-based technologies, a-Si:H and μc-Si:H single junction solar cells have been deposited on chemically etched substrates to assess the optical gain using MST. On the same type of substrates, a-Si:H/μc-Si:H tandem mini-modules have been fabricated. For CIGS technology, two deposition routes (1-stage and 3-stages coevaporation processes) have been first compared on flat reference substrates. The use microspheres textured substrates to increase current for ultrathin solar cells has been successfully tested for the 1-stage deposition route.

3.3.2 Main results of AGATHA project and potential impact and use

- **Si-based thin film solar cells**

a-Si:H, μc-Si:H single junction solar cells with reduced absorber thicknesses and a-Si:H/μc-Si:H tandem mini-modules (Fig. 3.1.3 (a)) with reduced top cell absorber thickness have been fabricated on chemically etched substrates. On these substrates, photovoltaic properties of devices always underperform results obtained on reference substrates and particularly as far as current is concerned. These results have been mainly attributed to unsuitable features sizes and aspect ratio obtained with this kind of texturation.

- **CIGS based solar cells**
  - *Role of Mo nanoparticles and Mo issue:* as demonstrated by optical simulations, absorption in the Mo back contact is a major drawback in the CIGS technology and particularly when texturation is brought to this layer. This has been particularly shown for Mo nanoparticles and as no positive impact of these particles were expected, they have finally not be used in solar cells.
  - *1-stage coevaporation process:* 3-stages coevaporation process is commonly used for the fabrication of CIGS solar cells. In the project, 1-stage coevaporated CIGS solar cells have demonstrated similar or even better power conversion efficiencies for devices with ultrathin absorber layers. A literature study has shown that production costs with this method are notably cheaper than with traditional process.
  - *CIGS solar cells on textured substrates:* CIGS solar cells have been deposited on microspheres textured substrates. Current enhancement up to 4.1 mA-cm^{-2} and efficiency gain up to 5% relative have been obtained. At long wavelengths, textured glass substrate implies light trapping in the absorber layer as demonstrated by External Quantum Efficiency (EQE) spectra depicted in Fig. 3.1.3 (b).

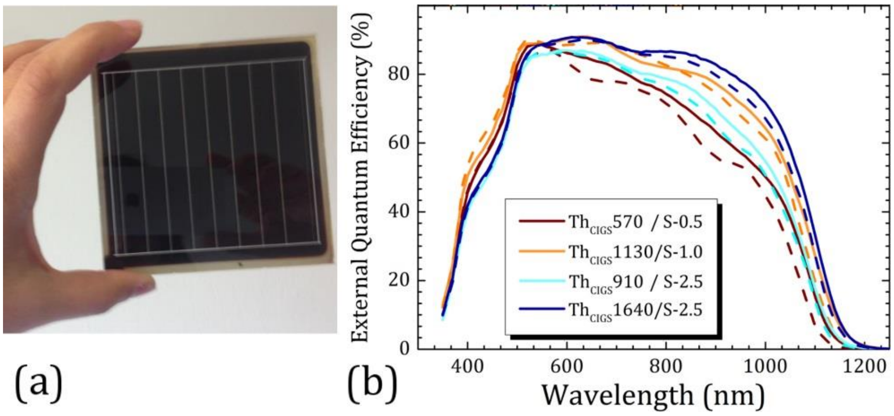

Figure 3.1.3: (a) Photography of a 10x10 cm2 a-Si:H/µc-Si:H minimodule on textured substrate. (b) EQE spectra of CIGS solar cells with different thicknesses (Th_{CIGS}) on microspheres textured substrates with different sizes (0.5 µm S-0.5, 1.0 µm S-1.0 and 2.5 µm S-2.5) (continuous lines) along with spectra on reference flat substrates (dashed lines).

In conclusion, AGATHA project achieved in producing different thin film (a-Si:H, µc-Si:H, tandem a-Si:H/µc-Si:H and CIGS) solar cells and minimodules as well as textured glass substrates. Implementation of devices with reduced absorber thicknesses on textured substrates led to current increase in the case of CIGS solar cells while no improvement was obtained for all Si technologies. The impact of such results is reduced by the fact that the beginning of the project was 3 years delayed and important efforts have been devoted by the European consortium to additional tasks (fabrication of textured substrates).

Due to the fast changes in the photovoltaic industrial environment in past few years, the 3 years delay for the project start seriously affected the potential economic impacts of AGATHA project. Particularly, from 2010 to 2013 (official start date), thin films Si technologies had to face an ever harsher competition in term of efficiencies and only tandem devices are currently on the market. The lack of improvement in devices efficiencies along with over costs due to substrates fabrication make this approach hardly suitable at the industrial level in 2016. Concerning CIGS, the use of textured substrates can be considered only if a parasitic absorption in Mo can be faced and demonstration of low cost textured substrates fabrication is made.

A public website has been created to present the objectives, the different partners as well as the main results and events organized within the AGATHA project: http://agatha-project.eu/.

Contact: Dr. Louis Grenet – CEA, 17 rue des Martyrs 38054 Grenoble Cedex 09 France – louis.grenet@cea.fr.