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Design and optimisation of process parameters in an in-line CIGS evaporation pilot system[☆,☆☆]

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ABSTRACT

Substantial efforts have been made globally towards improving $Cu(In,Ga)Se_2$ thin film solar cell efficiencies with several organisations successfully exceeding the 20% barrier on a research level using the three-stage CIGS process, but commercial mass production of the three-stage process has been limited due to the technological difficulties of scaling-up. An attempt has been made to identify these issues by designing and manufacturing an in-line pilot production deposition system for the three-stage CIGS process which is capable of processing 30 cm × 30 cm modules. The optimisation of the process parameters such as source and substrate temperature, deposition uniformity, flux of copper, indium, gallium and selenium and thickness control has been presented in this investigation. A simplistic thickness distribution model of the evaporated films was developed to predict and validate the designed deposition process, which delivers a comparable simulation compared with the experimental data. These experiments also focused on the optimisation of the temperature uniformity across 30 cm × 30 cm area using a specially designed graphite heating system, which is crucial to form the correct α-phase CIGS in the desired time period. A three-dimensional heat transfer model using COMSOL Multiphysics 4.2a software has been developed and validated with the help of experimental data.

1. Introduction

The development of thin film solar cells has gained significant importance due to better material utilization and reduction of the cost of the modules as compared to c-silicon, in an attempt to achieve grid parity [1–3]. However, there has been fierce competition offered recently by the c-Si technology, which has brought the module cost below $1/Wp [3]. Although, there is good scope for thin film technologies such as CIGS to increase the efficiency and bring the cost down further, it still remains a challenge to scale up the technology to achieve high performance of the modules on a production scale. This mainly stems from the optimisation of the process conditions to achieve control on the morphology and electronic parameters of the thin film layers from batch to batch production. Some organisations have made good progress in transferring state-of-the-art champion cell technologies to industrial production. Solar frontier has achieved 19.7% efficiency on approximately 0.5 cm^2 area CIS solar cell and 14.6% on 125.7 cm × 97.7 cm CIS module efficiency using the two-step process which requires toxic H_2Se vapour [4] for selenisation. Manz has also achieved a CIGS module efficiency of 14.6% with the help of a turn-key production line using the one-step process [5].

This in-line pilot system for high performance CIGS solar cells is the first system of its kind to address the three-stage CIGS process at a production level; a schematic representation of this system is given in Fig. 1. The three-stage process has the potential to yield the highest efficiencies in production as compared with the standard one- and two-step processes, because all of the champion cells are manufactured this way at a research level. However, it is the most difficult of the three processes to scale up. As presented here the pilot production system has a few significant advantages over existing one-step and two-step CIGS production systems.

It has been designed to avoid the use of highly toxic reactant gas H_2Se, which requires robust maintenance of the exhaust and trapping system such as an expensive scrubber along with a gas sensor alarm system to meet the safety standards of the process. In addition, the system also has a built-in flash evaporation unit which can be used to prepare the CdS buffer layer (including a range of alternative Cd free buffers). An obvious advantage lies in utilizing the vacuum deposition process

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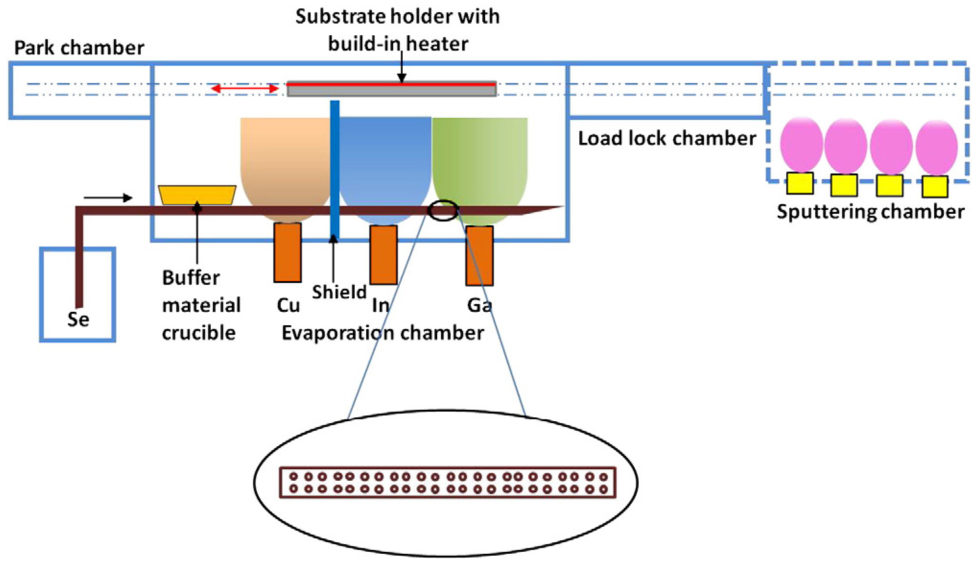

Fig. 1. A schematic of an inline co-evaporation CIGS system.

for all five layer stacks for finishing the CIGS solar cells, thereby reducing the total deposition time, without having to break a vacuum.

The standard system configuration consists of three interconnecting chambers as shown in Fig. 1, comprising a central dealer chamber with an evaporation chamber and sputter chamber connected either side and separately pumped. The substrate loading is controlled by a robotic arm which picks the substrate mounted in a holder from the load lock, and moves it along with the heater to provide local heating of the substrate. The substrate drive is controlled by a servomotor and encoder which allows the substrates to be accurately positioned and oscillate over each of the deposition zones achieving optimum film uniformity. On completion of the process development work, this system has the potential to be developed into an efficient industrially proven process for large scale production of CIGS which will yield a reduction in process time as compared with other energy intensive vacuum apparatus. Normally a significant amount of energy is wasted in breaking vacuum in order to transfer the substrates to perform other vacuum or non-vacuum processes.

Previously the three-stage process had been used to prepare small scale laboratory champion CIGS cells, but to scale up to an industrial level has not been attempted. This is because of several process issues such as heating the substrate to elevated temperatures whilst moving the substrate assembly to different areas of the process chamber for deposition of the various elements and the positioning of multiple deposition sources for each element to achieve uniform distribution of the deposition materials, as well as other process complexities. This in-line pilot system has been developed to grow CIGS layers using a three-stage process on glass substrates to address these scaling issues. In the first stage, the substrate traverses over the In and Ga effusion sources, where (In,Ga)Se is grown on the substrate maintained at 450 °C. In the second stage, the substrate traverses over the Cu effusion source, where $Cu_{2-x}Se$ phase is formed around 550 °C. In the third stage, the substrate is brought back to the In and Ga source zone where CIGS is grown on the substrate to form Cu-poor CIGS around 550 °C. By controlling the movement of the substrate, three-stage deposition process was achieved. It may be noted that a copious amount of Se vapour was used throughout the process. The efforts are underway to optimise the process for large area (up to 30 cm × 30 cm) uniform CIGS thin film deposition on glass substrate, using this machine.

The film uniformity is the key to scaling-up of CIGS solar cells. The thickness and composition uniformity are the primary requirements to achieve good optical and electronic properties for high performance solar cells. From a production point of view, uniformity directly impacts yield [6]. Therefore, for mass production of high efficiency and large area modules, high throughput and reproducible uniformity are crucial. A simple thickness distribution model from two-source evaporation has been developed to simulate the deposition process of each metal source and their thickness uniformity over a large area. This model was used to gain better understanding of the physical system and to predict the film growth. Another important requirement is the flux control which has been addressed as well with the help of the thickness distribution model. In this paper, an attempt has been made towards the development of uniform CIGS layers deposited over a 30 cm × 30 cm area with a specially designed heating assembly. The experiments were designed to validate and test the operational feasibility of an in-line three-stage deposition process. The optimisation was focused on the substrate temperature control and its distribution, which is one of the most important scaling-up requirements. To achieve uniform heating, a thermal model based on the heat transfer module of COMSOL 4.2a was developed and validated with the experimental results.

2. Modelling and experiments

2.1. Thickness and temperature distribution modelling

A simple thickness distribution model from two-source evaporation has been developed using Matlab 2008 to simulate the deposition process of each metal source and its thickness uniformity across a large area. Some process parameters such as source temperature and chamber pressure in the presence of selenium vapour are considered in this model. Besides, a three-dimensional finite-element thermal model was developed for the heat transfer process applied to the substrate with localised heating using COMSOL Multiphysics 4.2a software. The theory, boundary conditions and modelling details for both the parameters are presented in the Results and discussions section.

2.2. Experiments

The in-line pilot scale co-evaporation system (Fig. 1) consists of two deposition zones which are separated by a metal shield [7]. Ga and In sources in the second zone, whilst Cu sources are kept in the first zone. This has been done to avoid cross contamination. The base pressure of the evaporation chamber was maintained at ~10^5 Pa with a processing pressure of ~10^3 Pa. Most of the samples for testing were 5 cm × 5 cm and 10 cm × 10 cm mounted on a graphite substrate holder as shown in Fig. 2. The modelled thickness distribution was experimentally validated. The Cu layer was deposited in the first