Linear Thermal Evaporation Source for Large Area CIGS Solar Cell Manufacturing

Keqi Zhang and Ralph Faber

Vacuum Process Technology, LLC
70 Industrial Park Road, Plymouth, MA 02360, USA

ABSTRACT: CIGS solar cells with efficiencies greater than 20% have been fabricated in laboratories with co-evaporation. However, high volume manufacturing remains a challenge. One of the scaling issues is the lack of adequate evaporation technolgy that can deposit high quality copper films with high stability and uniformity across a large area. In this paper, a linear vapor source designed for evaporating copper and other metals for large scale CIGS photovoltaic solar cell manufacturing will be presented. The tool described in this paper is a top down thermal evaporation source with the capability of depositing uniform copper films on a large moving substrate. Defect free copper films with approximately ±3% thickness uniformity across a 120cm substrate have been achieved, along with up to 4 grams per minute of evaporation rate and less than ±2% of rate stability. Theoretical simulation indicates that a thickness uniformity of ±1.0% across a 120cm substrate can be achieved.

1 INTRODUCTION

Two types of technologies are currently used in the solar industry to develop and manufacture photovoltaic solar cells: 1) crystalline (or polycrystalline) wafer and 2) vacuum thin film coating. Due to the increasing demand for clean, renewable energies, both wafer and thin film based photovoltaic technologies have advanced considerably in recent years. However, with some clear advantages of vacuum thin film coatings [1], such as low material usage, large monolithic dimensions, and low cost manufacturing, thin film based solar cells are increasingly gaining market share [2].

Currently the leading commercial thin film technologies are CdTe, CIGS and polycrystalline silicon. Due to environmental, efficiency and cost considerations, CIGS appears to be the most promising one with the highest potential.

CIGS thin films are mainly deposited by two different PVD technologies: magnetron sputtering and thermal evaporation. However, the efficiencies of CIGS solar cells fabricated with thermal evaporation are consistently higher compared to sputtering. Co-evaporating Cu, In, Ga, and Se leads to larger crystal growth in the CIGS absorber layer which results in improved electrical transport properties of the solar cells. Further, the highest known efficiency of CIGS solar cells (20.3%) is produced by a co-evaporation process on a 0.5cm^2 cell [3]. The major objective for the solar industry is to overcome the scaling challenges of the production equipment, including the thermal evaporation technology, so that high efficiency CIGS solar cells can be realized at low cost.

The Linear Vapor Source developed by Vacuum Process Technology is specifically designed to address this scaling issue. It provides an effective tool for the solar industry to precisely deposit the required metals for the CIGS absorber layers, with a very stable evaporation rate and excellent uniformity.

2 DESIGN OF THE VAPOR SOURCE

The VPT Linear Vapor Source is a top down evaporation source which is used in production in-line coating systems to thermally evaporate metals and semiconductor materials for thin film solar photovoltaic applications. The source has the capability to deposit a 120 cm wide substrate uniformly with a dynamic deposition rate (for Cu films) of over 200nm m/min or static evaporation rate of 4.0 grams/min. Figure 1 is a schematic that shows the basic design concept of the Linear Vapor Source. Evaporation material, such as Cu, is heated in crucibles to a temperature range between 1250°C and 1450°C. The Cu vapor is then transported through the upper vapor channel into the vapor distribution channel. The evaporated Cu creates a high vapor pressure differential between the vapor distribution channel and the substrate area. The pressure at the substrate area is typically two to three orders of magnitude lower, therefore the Cu vapor is directed through the source exit slits and deposited from top down onto the moving substrate.

The Linear Vapor Source is designed to continuously operate in vacuum coating systems in a production environment to deposit high purity thin films. It is critical that proper refractory materials and ceramics are selected for the construction of the Vapor Source. This ensures that 1) the source materials are compatible with the evaporated materials (Cu, In, Ga and Se); and 2) there is no cross contamination between the source and the evaporated materials.

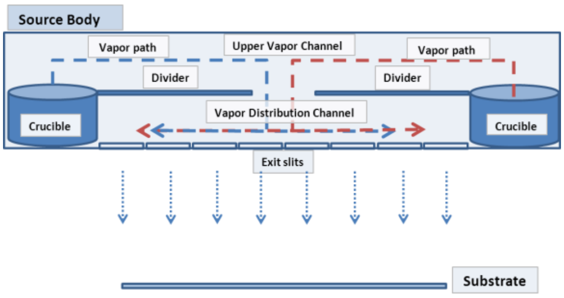


Figure 1: Schematic of the VPT Linear Vapor Source

Producing high efficiency CIGS solar cells is a complex process; many factors have to be taken into account which will affect the performance and efficiencies. One of the key issues in the fabrication process is to obtain a high quality CIGS absorber layer that has an optimal and homogeneous composition on a large scale substrate with high repeatability. As copper is one of the key elements in the CIGS absorber layer, it is critical that it can be deposited with a predictable and stable evaporation rate while maintaining excellent film uniformity.

Simulation shows that the Cu evaporation rate in vacuum is a function of its melted surface area and temperature. Figure 2 shows this relation. It is obvious that with a higher temperature and a larger melted surface area, the evaporation rate increases.

Based on simulation, if the Vapor Source is operated at around 1350°C to 1400°C, the source temperature needs to be accurately controlled within ±1°C in order to maintain a desired deposition rate stability of ±1.5%.

The uniformity of film thickness is an important factor to consider for large scale substrates of over one meter width. It is well known that in a physical vapor deposition process, thin film uniformity is primarily dependent on the relative location of substrate to evaporation source, the material properties, the deposition method and conditions and the geometry of the evaporation source. By considering all these factors, a simulation model was created to accurately predict the film thickness distribution in parallel and perpendicular to the vapor exit slits. In Figure 3 the simulation shows that it is possible to control the Cu film thickness uniformity within less than ±1.0% in the 1200mm center region parallel to the source exit slits. The uniformity declines rapidly at both ends of the exit slits which is the result of the edge effect of the evaporation source.

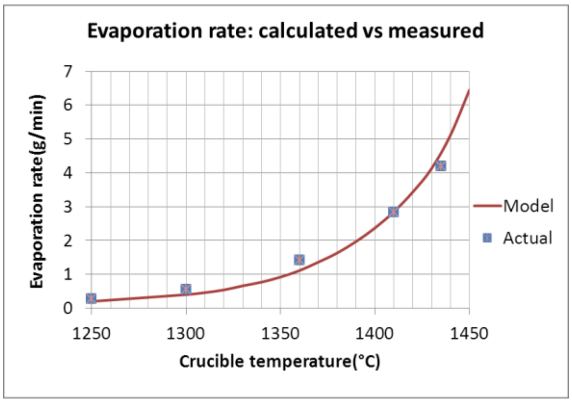


Figure 2: Cu evaporation rate of the Vapor Source: theoretical model versus actual.

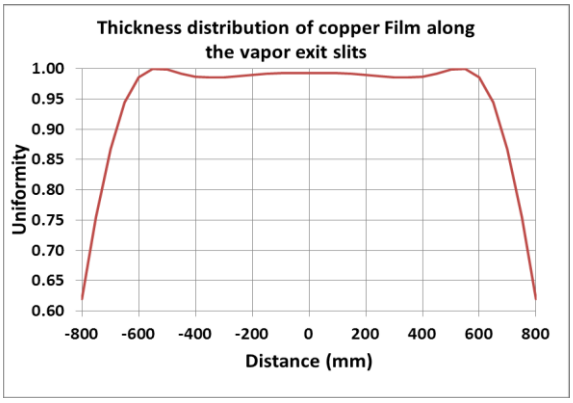


Figure 3: Simulated uniformity of the Vapor Source with ±0.7% thickness uniformity in the 1200mm center region.

Based on the discussion above, a top down Linear Vapor Source that is capable of thermally evaporating Cu and other metals for CIGS photovoltaic solar cells has been developed. The performance parameters of the vapor source are summarized in Table 1.

Table 1. VPT Vapor Source performance

Description	Value
Source dimension	
L(mm) × W(mm) × H(mm)	2100 × 400 × 400
or L(mm) × W(mm) × H(mm)	1500 × 400 × 400
Deposition method	In-line thermal evaporation
Deposition type	Top – down
Source exit slit to substrate distance(adjustable, mm)	300 -500
Substrate width (mm)	up to 1200
Source uniformity (source center to ± 600mm)	< ±3%
Static evaporation rate	
g/min	2 - 4
nm/s	5 - 10
Dynamic deposition rate (nm m/min, typical)	200
Evaporation rate stability	±2%
Source operating temperature - maximum (°C)	1450
Source temperature stability, crucible (°C)	±1
Source crucible capacity (cm³)	2400/4800
Source power consumption (kW)	80 – 100

3 EXPERIMENTAL RESULTS

The Vapor Source was developed and tested in a VPT vacuum deposition system which is equipped with turbo-molecular pumps and load locks. Oxygen free high conductivity (OFHC) copper with 99.99% purity is used as evaporation material. Cu is selected as testing material because it has the highest evaporation temperature of the elements used in CIGS and hence is the most difficult to process.

The vapor source was operated in a temperature range between 1250°C and 1450°C. The substrates are placed directly below the source exit slits at a throw distance of 400mm. The typical pressure in the process chamber during Cu evaporation was approximately 8×10^{-5} Torr. The reliability, stability, repeatability, film quality, and film uniformity were tested and verified. During many hours of operation it was found that the source had demonstrated excellent reliable and repeatable performance, and fully met the specifications listed in Table 1.

3.1 Temperature stability

As discussed, an accurate and stable crucible temperature is critical to maintain the Cu evaporation rate stability. Figure 4 shows the recorded temperatures of the two crucibles during operation. The crucible temperatures are controlled within ±1°C over a long period of time.

3.2 Thickness uniformity, repeatability and evaporation rate of the Cu film

Uniform Cu films were achieved over a very large area. Figure 5 shows the measured Cu film thickness distribution of four deposition runs over a 24 hours period with a uniformity of < ±3%. Uniformity is defined as the difference of maximum and minimum film thickness of all runs divided by the average thickness. The thickness repeatability, which is an indication of the evaporation rate stability is +/- 1.6%.

In addition to the Cu thickness uniformity along the exit slits, it is also important to know the relative thickness distribution of Cu film perpendicular to the exit slits. The Cu thicknesses that are perpendicular to the center of the exit slits are

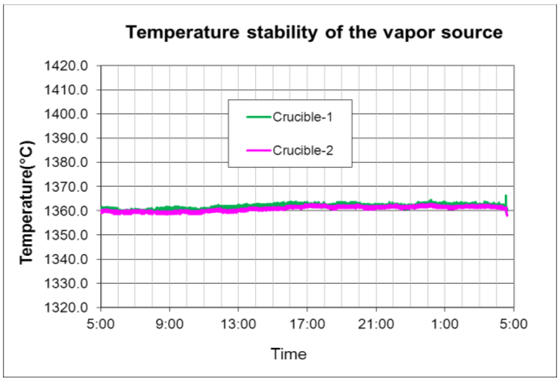


Figure 4: Recorded vapor source temperature over 24 hour period during its operation.

measured. Figure 6 shows the actual measured result. Using the simulation model previously mentioned, it is found that the linear vapor source discussed here has a $\cos^4(\theta)$ vapor distribution when Cu is evaporated with a temperature of approximately 1360°C.

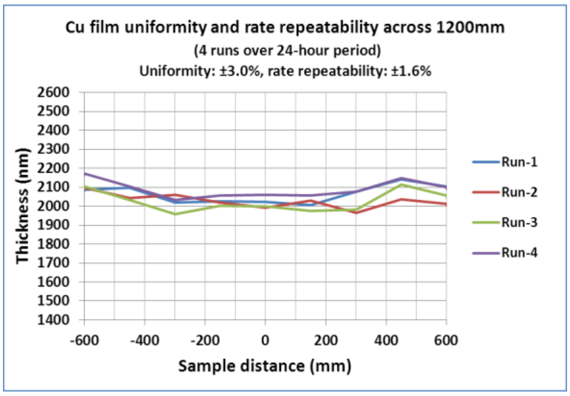
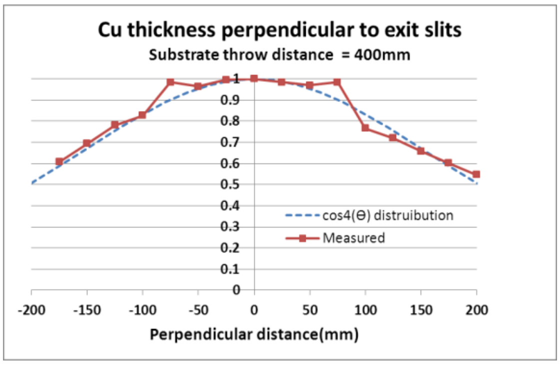


Figure 5: Thickness uniformity and repeatability of Cu films



.

Figure 6: Thickness distribution of Cu film perpendicular to the center of exit slits. Compared to the theoretical model (dash line), the Cu vapor plume has a $\cos^4(\theta)$ distribution.

The vapor source has been tested with temperatures ranging from 1250°C to 1450°C. Evaporation rates at distinct temperatures were verified and compared with the theoretical model. Figure 2 shows the comparison. The actual evaporation rate fits well with the theoretical model.

The response of the vapor source to temperature changes has also been tested. A set of crucible temperatures with small increments of approximately 1°C at around 1360°C are applied to the source crucibles. Cu films are then deposited for 10 minutes after the temperatures were stabilized. Figure 7 shows the relative evaporation rate of the Cu film versus crucible temperature in a small temperature scale. It confirms that a temperature change in the crucible of 1°C results in more than 1% change of the evaporation rate.

.

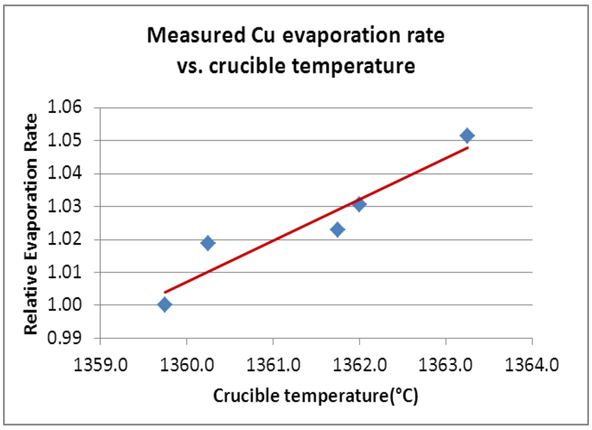


Figure 7: Measured relative evaporation rate of the vapor source versus small changes in crucible temperature.

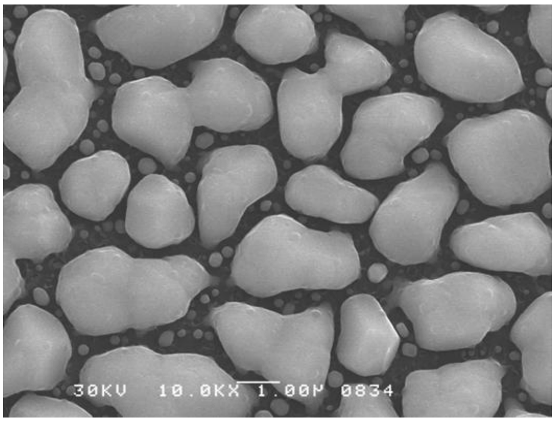


Figure 8: SEM analysis of Cu film evaporated by the Linear Vapor Source Cu film shows single crystal structure.

3.3 Surface morphology of the Cu film

Defect free copper films with excellent uniformity have been consistently achieved. Figure 8 is an SEM image of a 1µm thick Cu film. The deposited Cu film is mainly consisting of small single crystals in micrometer size.

4 CONCLUSION

A large scale linear vapor source which is capable of thermally evaporating copper and other metals in an in-line coating system for CIGS photovoltaic solar cell applications has been developed. It is demonstrated that high quality, defect free copper films with excellent uniformity over a 120cm area can be realized.

5 ACKNOWLEDGEMENT

The authors would like to acknowledge the following individuals of their contributions to this Linear Vapor Source development project: Ronald Crocker, James Snyder, and Joseph Patrinostro.

6 REFERENCES

[1] M. A. Green: Appl. Phys. A (2009) 96: 153-159
[2] H. S. Ullal and B. von Roedern: 22nd European Photovoltaic Solar Energy Conference and Exhibition, Milan, Italy, September 3-7, 2007
[3] "ZSW sets another new CIGS solar cell record", PV Tech – www.pv-tech.org, August 23, 2010.