Optimization of Anti-reflective Coatings for CIGS Solar Cells via Real Time Spectroscopic Ellipsometry

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Abstract **— In this study, we have optimized the anti-reflective coating for $Cu(In_{1-x}Ga_x)Se_2$ (CIGS) absorbers. The structure of the CIGS solar device has been intensively monitored using in-situ spectroscopic ellipsometry, and the thickness has been optimized to optically enhance the performance of the device. Various simulation techniques have been employed to optimize the thickness of the AR coating and this modeling has been correlated with experimental results to obtain the highest efficiency for the device. The overall efficiency has increased approximately by 5% with the new optimized AR coating and the device parameters for the best cells are reported.**

Index Terms **— CIGS, AR coatings, ellipsometry, optical films, photovoltaic cells.**

I. Introduction

The first reflection losses in a solar cell structure occur at the glass-air interface and about 4% of the solar energy is lost at the surface, in the absence of an effective light trapping technique [1]. Anti-reflective (AR) coatings are widely used for optical enhancement by minimizing the overall reflection losses and thus increasing the power conversion efficiency of the device. Destructive interference occurs among the reflected wavefronts, which reduces the reflectance; this is the basic mechanism of AR coatings. The simplest effective AR structure incorporates a single layer coating of thickness equal to one quarter times the wavelength within the coating and of refractive index given as the geometric mean of those of the ambient and substrate as described next [2].

Magnesium fluoride (MgF_2) is the most widely used material for AR coatings in CIGS solar cells because it forms high quality films and has a low refractive index n in order to meet the geometric mean condition [3]. The thickness of the AR coating should be chosen such that destructive interference occurs between the light reflected from the CIGS module interface and the AR coating surface and in this way reflections at the specific design wavelength are eliminated. This leads to the condition that the AR layer thickness should equal one quarter of the wavelength within the coating, or $d = \lambda/4 = \lambda_0/4n$, where λ_0 is the wavelength of the wave in vacuum [1]. It is therefore crucial to optimize the thickness of the AR layers to obtain higher efficiency for CIGS devices.

Spectroscopic ellipsometry is a very powerful tool to optimize the material properties as well as to monitor the process of deposition. Real time spectroscopic ellipsometry (RTSE) was implemented here to monitor not only film deposition, but also the reflected irradiance of the device during the deposition. This allows monitoring of the changes in reflectance from the structure and thus optimizing of the AR coating thickness.

II. Experimental Details

The optical properties and structure of each individual layer in the CIGS solar cell structure were characterized using ex-situ spectroscopic ellipsometry (SE). The optical properties thus obtained were used to model the reflectance, transmittance and absorbance losses in each layer. MgF_2 was chosen as the material for AR optical coating on top of the CIGS solar cells. The film was deposited by e-beam evaporation on well-characterized silicon wafers. The index of refraction and extinction coefficient of the material, as deduced by SE, are shown in Fig. 1.

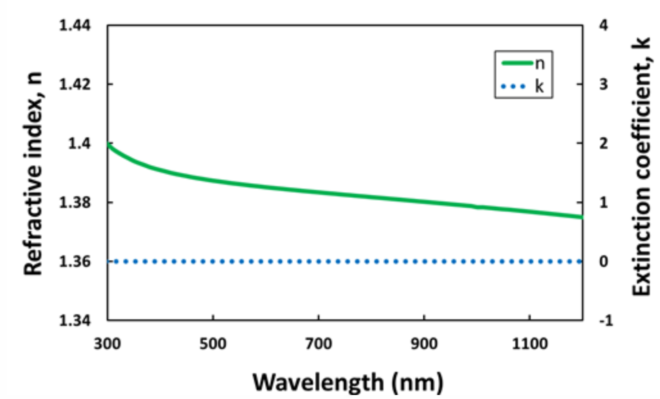

Fig. 1. Index of refraction *n* and extinction coefficient *k* for MgF_2, as deduced by ex-situ variable angle of incidence spectroscopic ellipsometry measurements.

An optimization model was developed based on the reduction of average reflectance, thus maximizing the optical absorption in the active layer. The modelling was performed for a CIGS absorber layer of thickness 2.5 μm with one layer of MgF_2. The average reflectance of the solar cell structure was calculated by [4]

$$R = \frac{1}{(\lambda_{\max} - \lambda_{\min})} \int_{\lambda_{\min}}^{\lambda_{\max}} R(\lambda) d\lambda \qquad (1)$$

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The MgF_2 layer was deposited on the CIGS solar cell by e-beam evaporation and variations in reflectance were obtained for different wavelengths during the course of deposition. The RTSE measurements were carried out *in-situ* during film growth using a rotating compensator, multichannel instrument with an energy range of 0.75–6.5 eV at an angle of incidence of 65°.

III. RESULTS AND DISCUSSION

The reflectance of the layers were closely monitored in-situ during the deposition of the AR coating on the CIGS device. Fig. 2 shows real time measurements of the relative reflectance from the multi-layered CIGS solar cell during the deposition of MgF_2. The variations in reflectance can be observed for different wavelengths during the course of the deposition. The reflectance reaches a minimum at the deposition of an optimum thickness near 7-9 minutes, ensuring that the reflectance of the structure is a minimum.

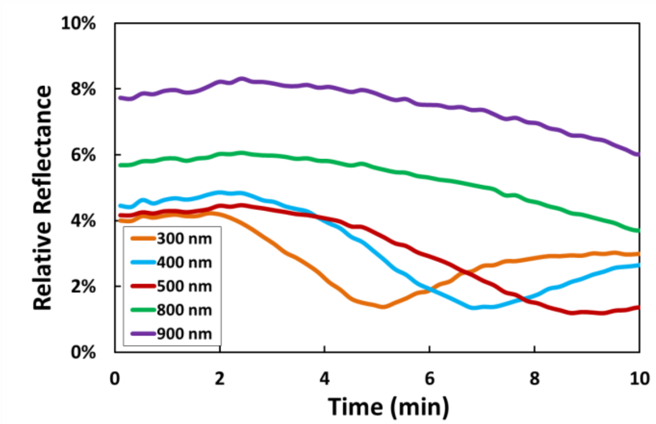

Fig. 2. Real time variation of the relative reflectance during the course of deposition of the AR layer (t = 0 to 10 min).

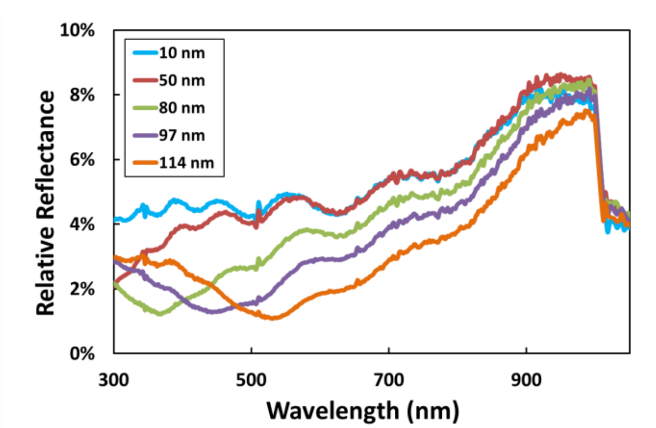

Fig. 3. Variation of reflected irradiance of the CIGS structure with the thickness of the AR layer.

Fig. 3 shows the reflectance spectra of the device for different thicknesses. It is clearly evident that, at the optimum thickness of 114 nm, the average reflectance falls to a minimum. This correlates well with the quarter wave principle in order to achieve the desired path difference between the reflected beams required to attain destructive interference.

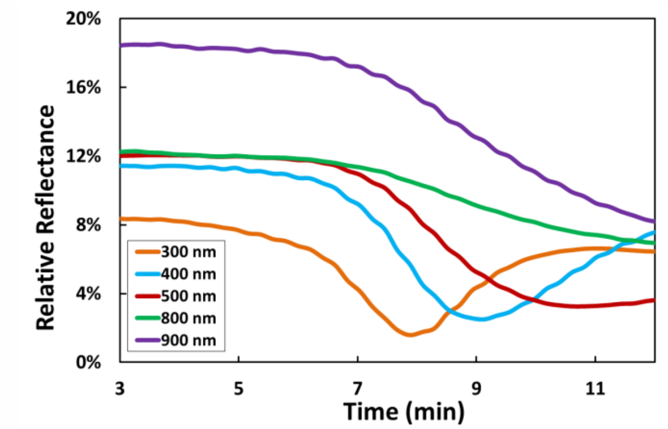

Fig. 4. Real time variation of the relative reflectance during the course of deposition of the AR layer for longer time periods (t = 3 to 12 min).

The thickness of the AR layer was further increased and the variation of the reflected irradiance during the course of deposition was monitored (Fig. 4). With a large thickness of AR coating, the reflected irradiance seems to curve upward, thus increasing the reflection losses of the device. Fig. 5 clearly shows the increase in reflected irradiance with respect to the thickness of the AR layer. The average reflectance slowly increases, beyond the optimum thickness (114nm), with increased deposition time of MgF_2.

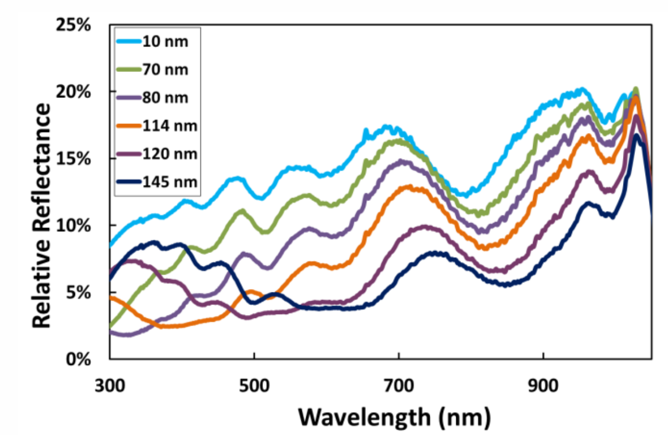

Fig. 5. Variation of relative reflectance of the CIGS structure with increased thickness of the AR layer.

The optical interference and absorption in the multi-layer stack was calculated using a model developed on a Matlab platform. The electric field profiles and thus the light absorption in each layer of the device structure were determined by assuming coherent propagation of optical plane waves without scattering [5]. This optical model was applied to predict the maximum obtainable J_{sc} values for the CIGS cells by varying the thickness of the AR layer and by assuming an IQE of 100%. The variation of J_{sc} versus the thickness of the AR layer is

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shown in Fig 6. The drop in J_{sc} beyond the optimum thickness value can be correlated with the increase in reflection losses (Fig 4). The maximum J_{sc} is observed for an MgF_2 layer of thickness around 114nm.

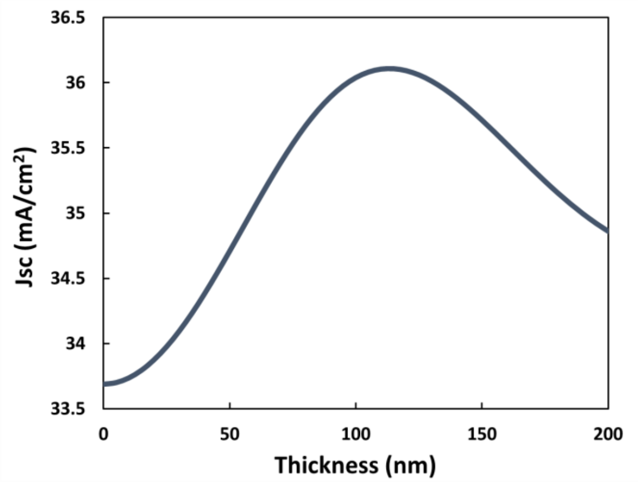

Fig. 6. Variation of short circuit current density of the CIGS device with increased thickness of the AR layer.

TABLE I

J-V PARAMETERS OF SOLAR CELL BEFORE AND AFTER APPLYING THE AR COATING

AR COATING	η (%)	Jsc (mA/cm^2)	Voc (V)	FF (%)
MgF_2	15.5	36.1	0.62	69.9
Without AR	14.6	33.9	0.61	71.0

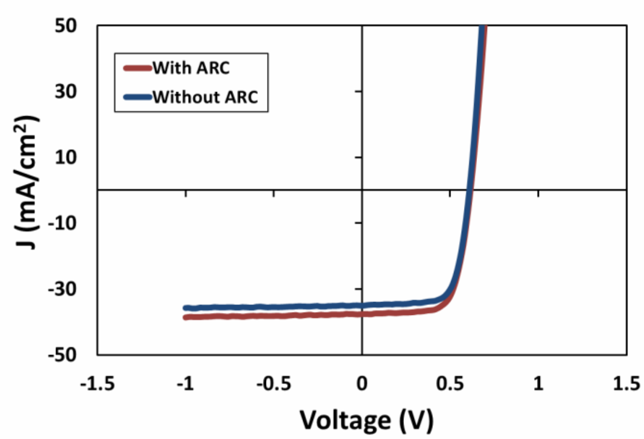

Fig. 7. Comparison of JV curves obtained for CIGS solar cells with and without the AR coating.

The thickness of the MgF_2 AR layer was decided upon using the in-situ reflectance measurement and simulation results. These results were incorporated into the fabrication of the AR coated CIGS device and a comparison of the effect of AR coating on the JV parameters of the recorded best cell is listed in Table I. The JV – QE results of the best cell with the new optimized coating is shown in Fig. 7 and Fig. 8. The experimental results are in good correlation with the modeling results.

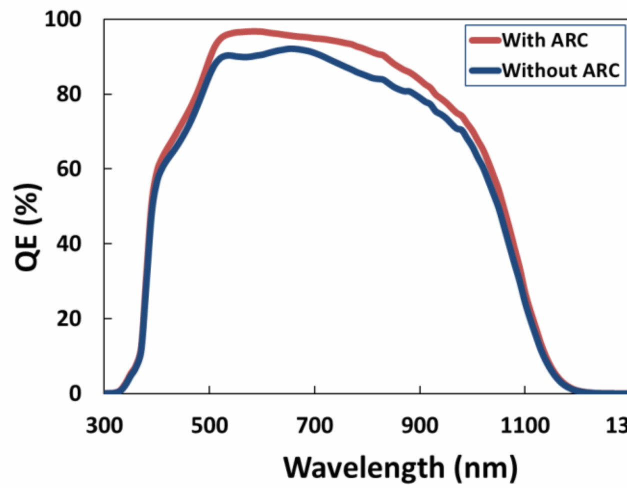

Fig. 8. Comparison of QE spectra obtained for CIGS solar cells with and without the AR coating.

Another optical model was developed incorporating the data obtained from RTSE and ex-situ ellipsometry to simulate the quantum efficiency of the CIGS device. The reflectance obtained during RTSE and the optical properties of each layer were incorporated to calculate the incomplete collection of photogenerated carriers in the CIGS device structure and is given by [6]

$$QE_{ext}(\lambda, V) = [1 - R(\lambda)][1 - A_{ZnO}(\lambda)] * [1 - A_{CdS}(\lambda)]QE_{int}(\lambda, V) \quad (2)$$

where R is the total reflection, A_{ZnO} is the absorption in the ZnO layer, A_{CdS} is the absorption in the CdS layer and QE_{int} is the internal quantum efficiency approximated by [7]

$$QE_{int}(\lambda, V) \approx 1 - \frac{\exp[-\alpha(\lambda)W(V)]}{\alpha L + 1} \quad (3)$$

where α is the absorption coefficient of CIGS, W is the space charge width in the CIGS layer and L is the minority carrier diffusion length. This approximation assumes that all the carriers generated in the space charge region are collected without recombination loss. The optically simulated QE spectra is compared to the measured QE spectra for the CIGS solar cell device with AR coating in Fig. 9, showing that the model provides a good fit.

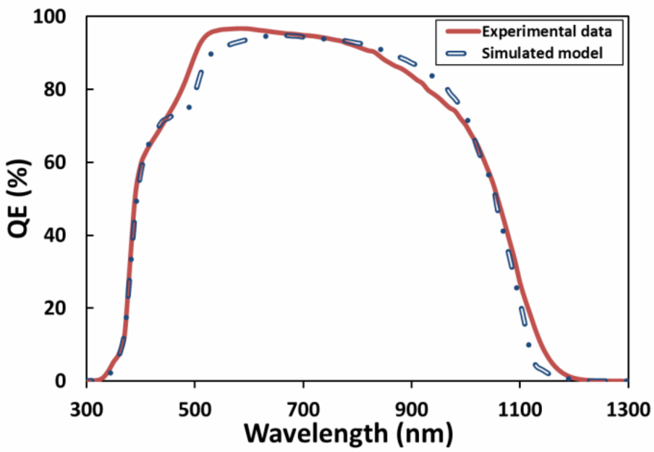

Fig. 9. Comparison of the measured and optically simulated QE spectra for CIGS solar cells

VI. Conclusion

The critical influence of the thickness of the AR coating for CIGS applications was demonstrated via modeling and experimental results. Real time spectroscopic ellipsometry was used to analyze the average reflectance of the CIGS structure to obtain optimum results. The efficiency of the CIGS solar cell increased by approximately 5% with the new optimized AR coating. The empirical results can be well correlated with the RTSE measurements and the optical simulations. In future, these different methods can be integrated to optimize the different layers of the CIGS solar cell devices and also can be applied to ultra-thin CIGS structures.

Acknowledgement

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References

[1] P.M. Kaminski, F. Lisco and J.M. Walls, "Multilayer broadband anti-reflective coatings for more efficient thin film CdTe solar cells," *IEEE J. Photovoltaics*, vol. 4, no. 1, pp. 452-456, 2014.

[2] P. Nubile, "Analytical design of antireflection coatings for silicon photovoltaic devices," *Thin Solid Films*, vol. 342, no. 1-2, pp. 257-261, 1999.

[3] P. Jackson, D. Hariskos, E. Lotter, S. Paetel, R. Wuerz, R. Menner, W. Wischmann, and M. Powalla, "New world record efficiency for Cu(In,Ga)Se_2 thin film solar cells beyond 20%," *Progess Photovoltaics: Res. Appl.,* vol.19, pp. 894-897, 2011.

[4] F. Chen and L. Wang, "Light trapping design in silicon-based solar cells" in *Solar Cells -- Si Based Technologies*, edited by L. A. Kosyachenko (Intech, New York, 2011), Chapter 12.

[5] J. S. C. Prentice, "Coherent, partially coherent and incoherent light absorption in thin-film multilayer structures", *J. Phys. D: Appl. Phys*, vol. 33, pp. 3139-3145, 2000.

[6] W.N. Shafarman and L. Stolt, "Cu(InGa)Se_2 solar cells" in *Handbook of Photovoltaic Science and Engineering,* edited by A. Luque and S. Hegedus, (John Wiley & Sons, Ltd., 2003).

[7] A. Fahrenbruch, R. Bube, *Fundamentals of Solar Cells*, (Academic Press, New York, 1983).