MgF_2/Ta_2O_5 Anti Reflective Coating Multilayers for AM0 Solar Cells

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I. Project Objectives

Goal: Show increased quantum efficiency (QE) with MgF_2/Ta_2O_5 bi-layer Anti Reflective Coating (ARC)

- Determine optimal material thicknesses for a minimum average reflectivity using a matrix approach in MATLAB.
- Develop a reactive sputter process for Ta_2O_5 using the CVC601 in SMFL.
- Use QE measurements of a commercial solar cell both with and without the designed bi-layer ARC to demonstrate improved device performance.

II. ARC Design By Method of Resultant Waves

Boundary Conditions[1]

$$r_{i-1} = \frac{n_{i-1} - n_i}{n_{i-1} + n_i}$$

$$t_{i-1} = 1 - r_{i-1}$$

$$\delta_i = \frac{2\pi d_i n_i}{\lambda}$$

$$E_+^i = \frac{E_+^{i+1} + r_i E_-^{i+1}}{t_i}$$

$$E_-^i = \frac{r_i E_+^{i+1} + E_-^{i+1}}{t_i}$$

Electric Field for m Dielectric Films[1]

$$\boldsymbol{I_i} = \begin{bmatrix} \frac{1}{t_i} & \frac{r_i}{t_i} \\ \frac{r_i}{t_i} & \frac{1}{t_i} \end{bmatrix} \quad \boldsymbol{T_i} = \begin{bmatrix} e^{i\delta_i} & 0 \\ 0 & e^{-i\delta_i} \end{bmatrix}$$

$$\boldsymbol{M} = \boldsymbol{I_0} \times \boldsymbol{T_1} \times \boldsymbol{I_1} \times \boldsymbol{T_2} \times \cdots$$

$$\cdots \times \boldsymbol{I_{m-1}} \times \boldsymbol{T_m} \times \boldsymbol{I_m}$$

$$\begin{pmatrix} E_+^0 \\ E_-^0 \end{pmatrix} = \boldsymbol{M} \begin{pmatrix} E_+^f \\ E_-^f \end{pmatrix} \quad \begin{pmatrix} E_+^f \\ E_-^f \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$n_0 | n_1 | n_2 | n_g =$$

$$n_{air} | n(\lambda)_{MgF_2} | n(\lambda)_{Ta_2O_5} | n(\lambda)_{Si}$$

Average Broad Band Reflectivity[1]

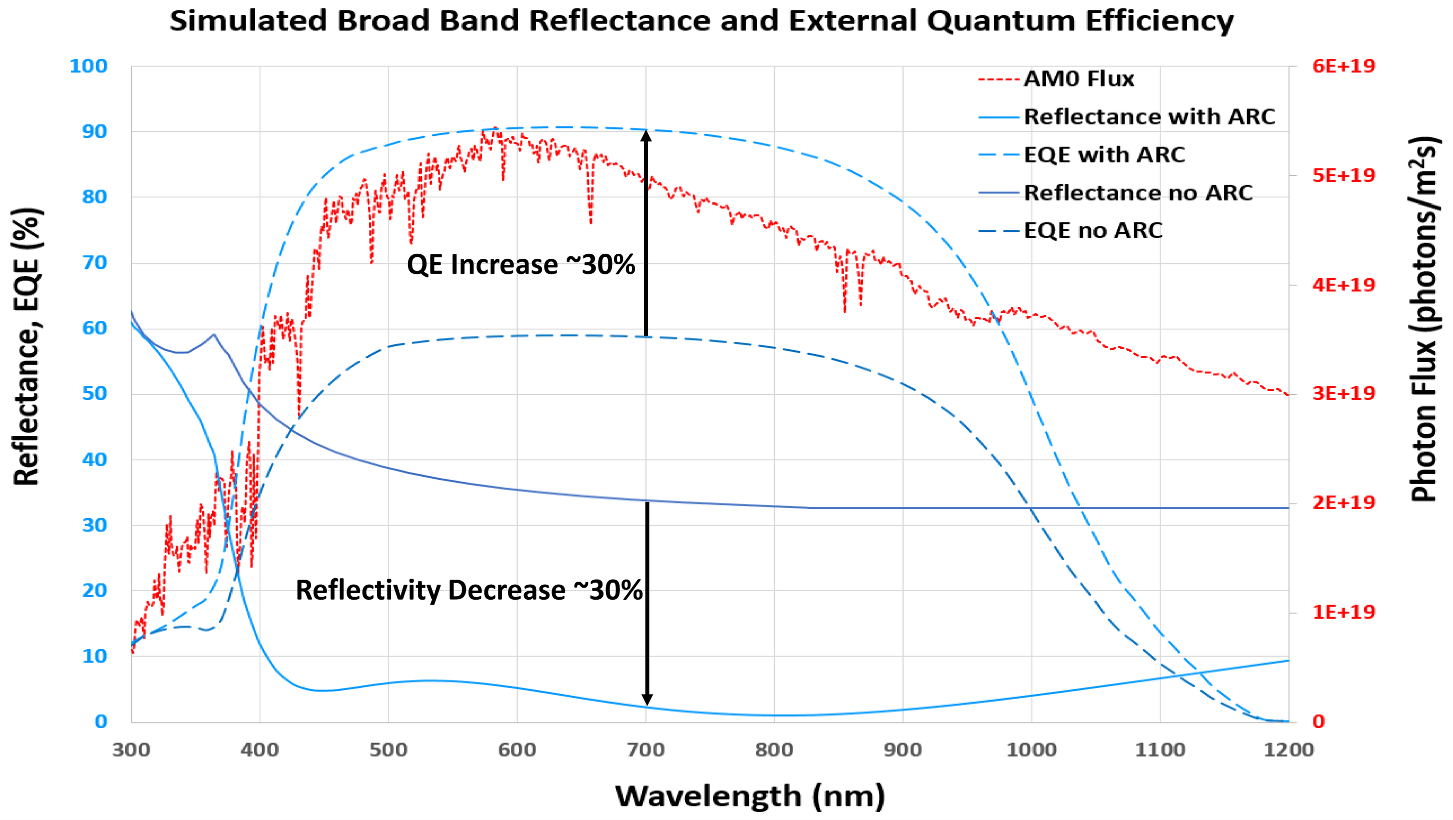
$$\rho = \frac{E_-^0}{E_+^0} \quad R(\lambda) = |\rho||\rho^*|$$

$$AM0\ Flux = F(\lambda) \quad R_e = \frac{\int_{\lambda_1}^{\lambda_2} F(\lambda) R(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} F(\lambda) d\lambda}$$

λ – wavelength
n – Complex index of refraction as a function of λ
r – Reflectance Fresnel coefficient
t – Transmission Fresnel coefficient
δ – Change in phase of light through a medium
d – Stack layer thickness
E^+ – Transmitted component of the light's electric field
E^- – Reflected component of the light's electric field
ρ – Stack reflectance coefficient
R_e – Average stack reflectivity for a range of λ

The method of resultant waves was modeled in MATLAB where an iterative approach was used to determine the thickness combination (d_1 and d_2) that exhibited the lowest theoretical R_e. A normal angle of incident light was assumed. The reflectance data was input to PC1D where simulations were run to show the theoretical increase in external quantum efficiency of a silicon solar cell under Air Mass Zero (AM0) spectral irradiance[2],[4].

Simulated Broad Band Reflectance and External Quantum Efficiency



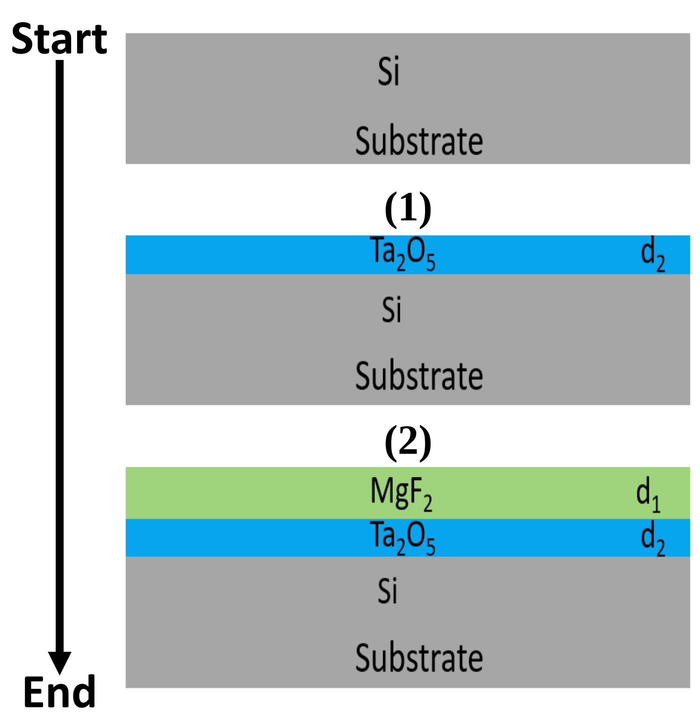
III. MgF_2/Ta_2O_5 Bi-layer Deposition Process

(1) Ta_2O_5 Reactive Sputter in CVC601

- 4" Tantalum target
- Base Pressure 5 mTorr
- 33% O2 to Ar gas mixture
- 400W DC Power during deposition
- Deposition rate ~6 Å/s
- 117 second DC sputter
- Target thickness 70 nm

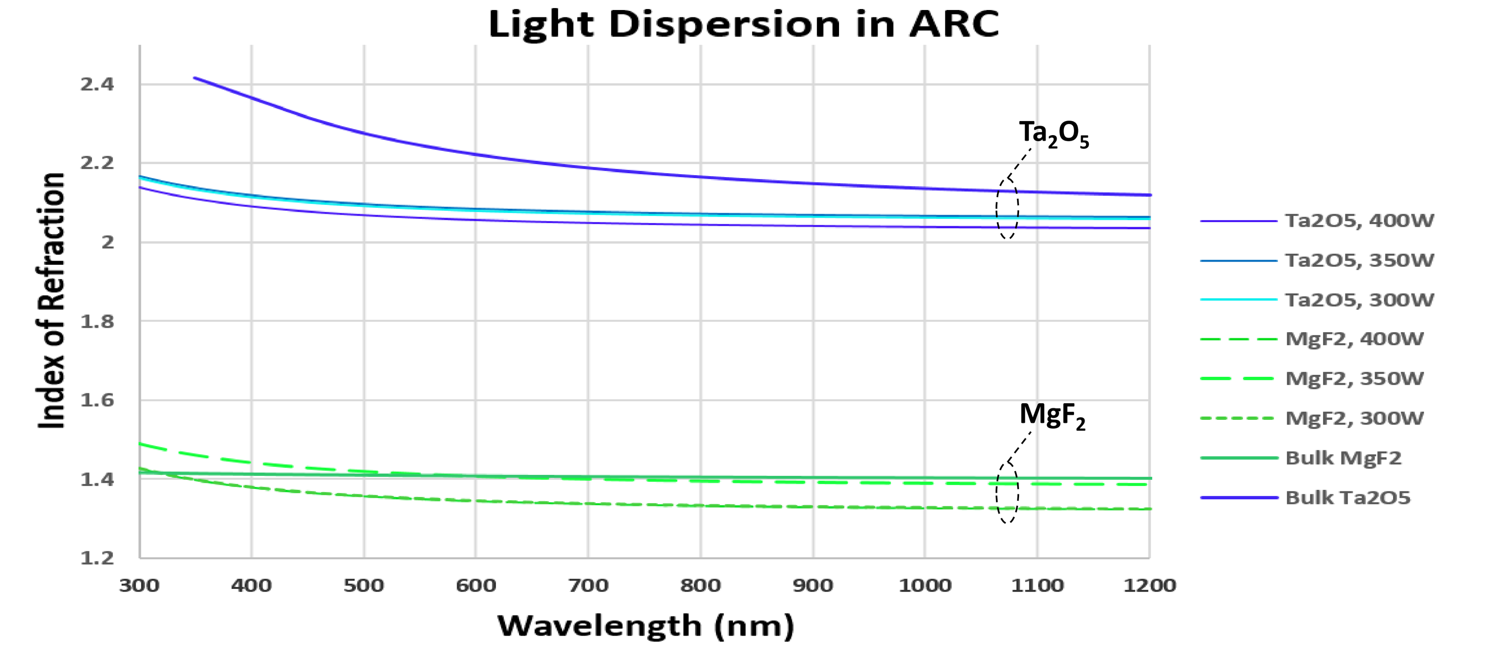
(2) MgF_2 Thermal Evaporation in PVD75A

- MgF_2 crystals loaded in Mo boat
- Followed Brittany Smith's process
- Spacers added under samples to minimize the effect of bloom adding to thickness non uniformity
- Deposition rate ~3-4 Å/s at 95% source power
- Target thickness 105 nm or 0.105 kÅ
- Reflectometry (Filmetrics Reflectometer) technique was used on a glass monitor slide to confirm thicknesses



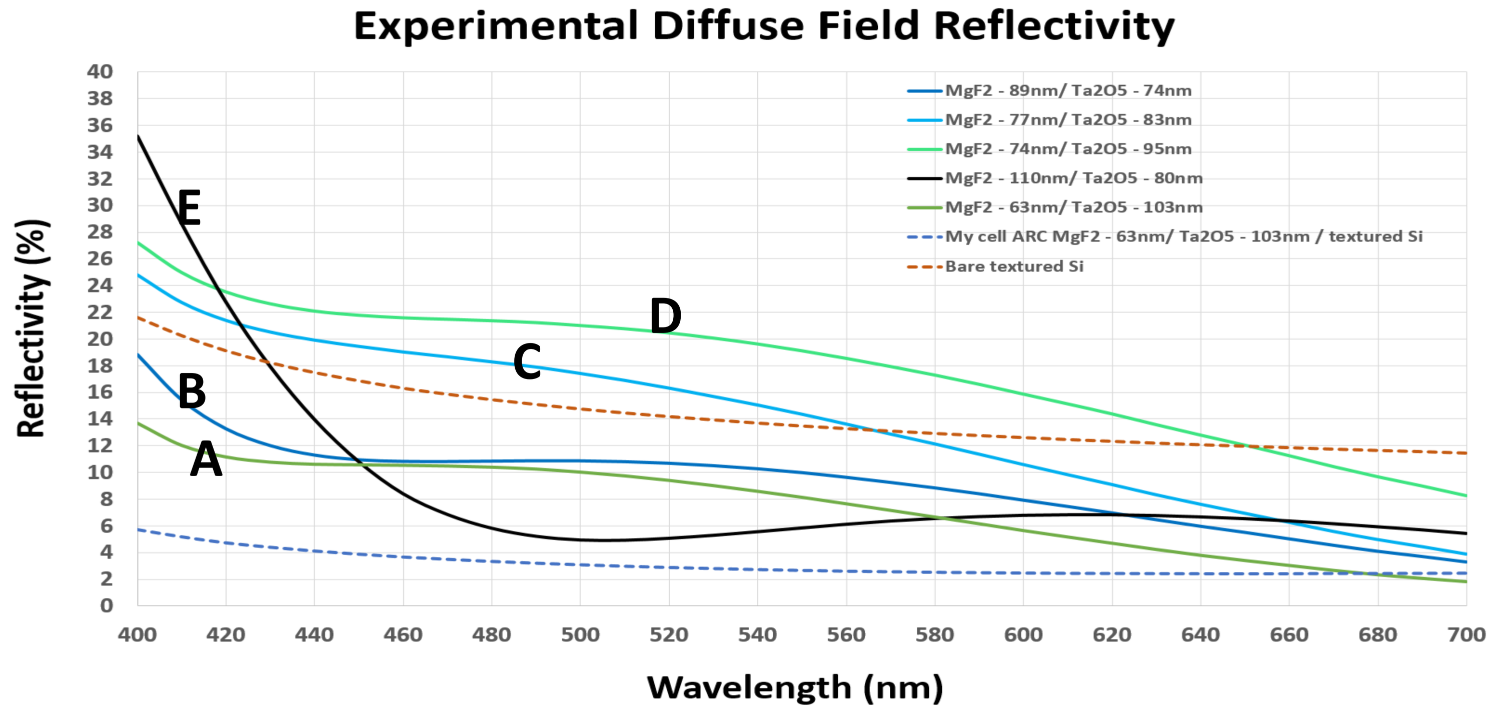
IV. Experimental Results

Light Dispersion in ARC



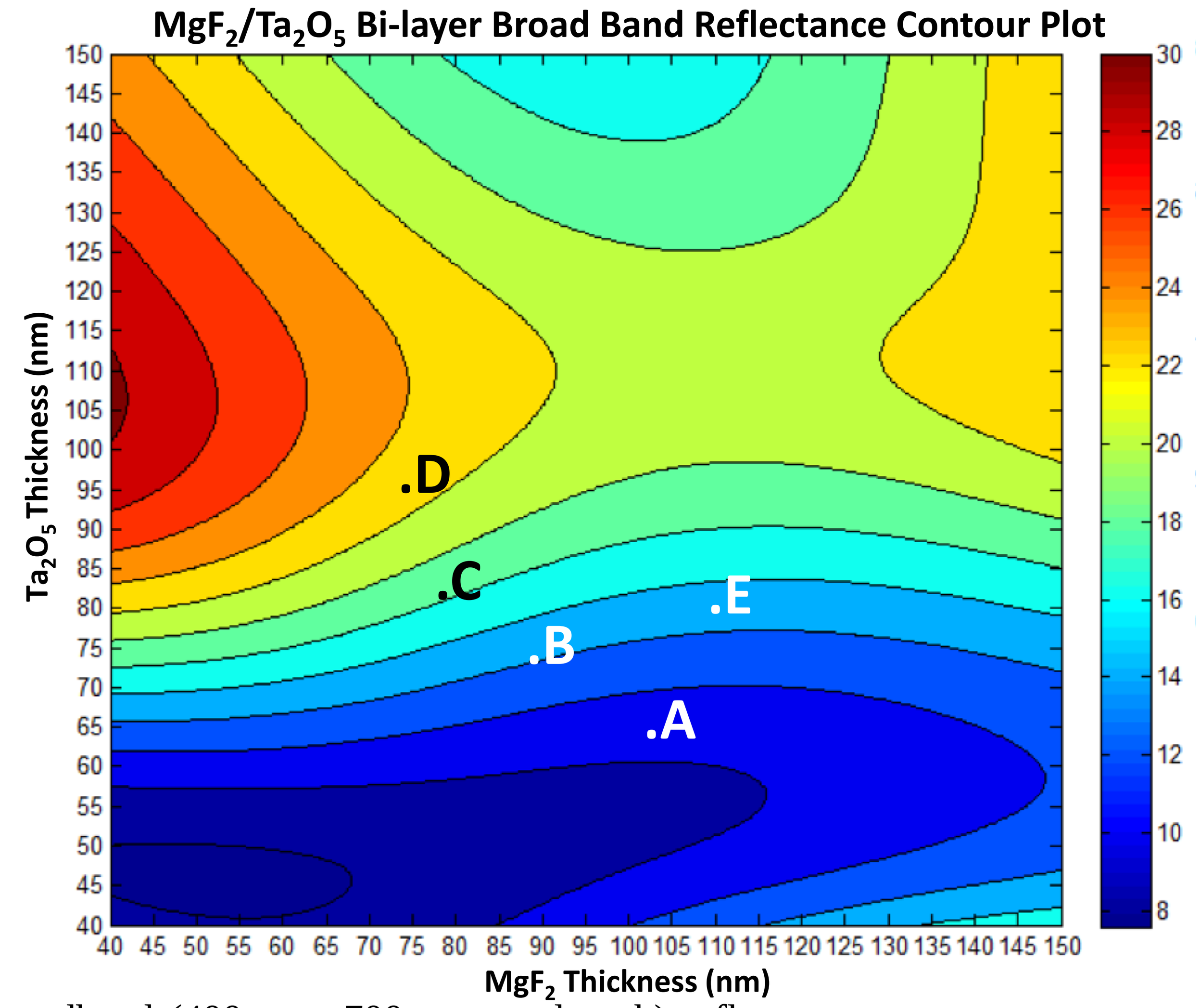
The refractive index values of each layer were determined using the WVASE with the exception of the bulk refractive index values[3]. The tantalum oxide films were measured for different sputter deposition powers. Each subsequent magnesium fluoride deposition was done for the same conditions on each sample because it is a well refined process. `

Experimental Diffuse Field Reflectivity



The reflectivity measurements of each film on silicon was made using a diffuse field integrated sphere reflectometer at the University of Rochester with the help of Dr. Jennifer Kruschwitz. The efficacy of the MATLAB simulations were tested when compared to measured results (**A** through **E**).

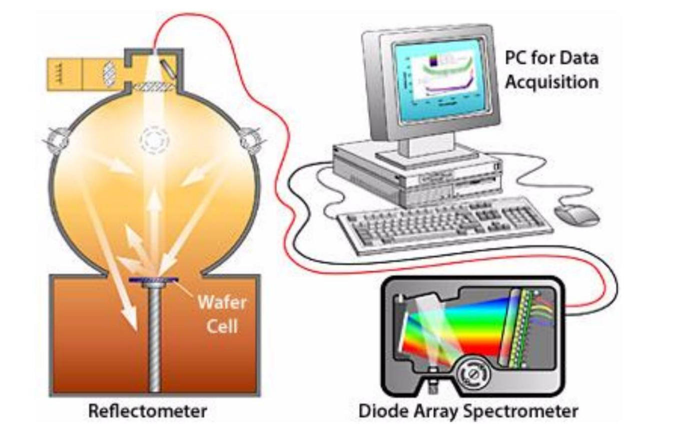
MgF_2/Ta_2O_5 Bi-layer Broad Band Reflectance Contour Plot



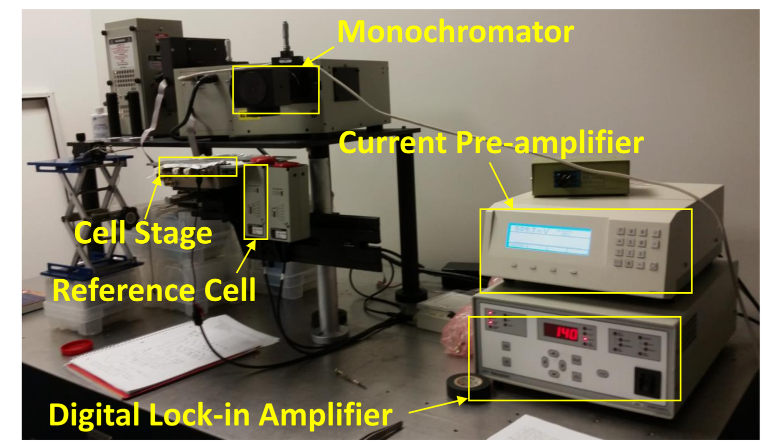
A broadband (400nm – 700nm wavelength) reflectance contour map was made using average reflectivity values for varying thicknesses in a 301x301 mesh grid. Plot points **A**, **B**, **C**, **D**, and **E** on the contour plot represent the thickness combinations from five different film depositions with average reflectance calculations of 7.2%, 8.9%, 13.2%, 17.4%, and 8.1% respectively. When the bi-layer films were mapped on the contour plot, the diffuse field reflectance measurements showed a similar trend.

Solar Cell Testing Results

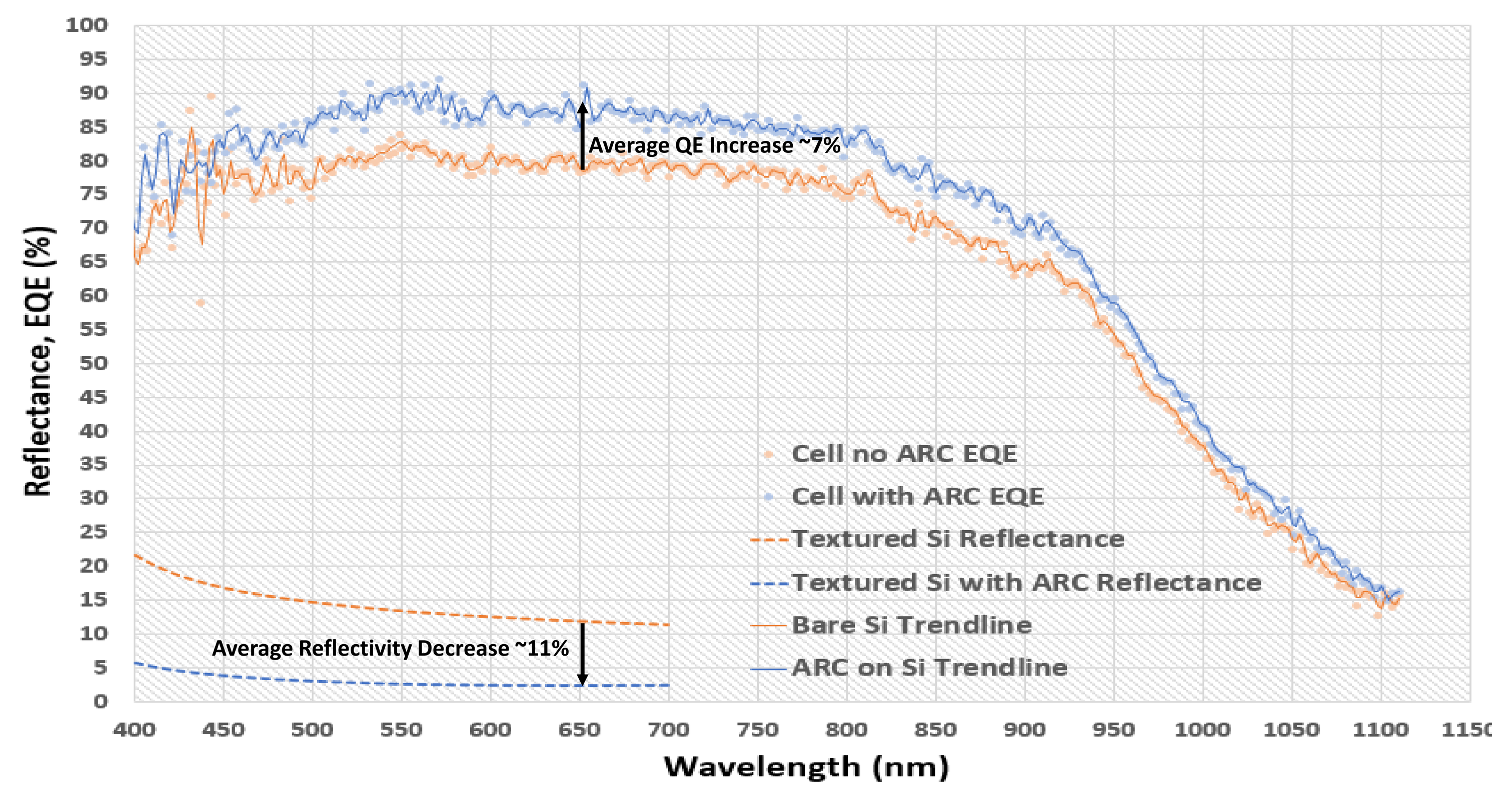
Diffuse Field Reflectance Setup[5]



QE Experimental Setup



Experimental Bi-layer ARC on c-Si Solar Cell



V. Conclusions

The optimal thicknesses of the bi-layer materials for the lowest average reflectivity under AM0 spectral irradiance were determined to be 105 nm of MgF_2 on top of 70 nm of Ta_2O_5 through modeling broadband reflectance by applying the method of resultant waves in a MATLAB script. This ARC was successfully deposited with reactive sputter and thermal evaporation techniques using design of experiments to determine the process conditions. The MgF_2/Ta_2O_5 bi-layer ARC resulted in an average reflectivity decrease by 11% and increased the quantum efficiency by 7% in a commercial c-Si solar cell for wavelengths ranging from 400 nm to 700 nm.

Future Work

- Utilize e-beam evaporation and deposit on dynamic substrates
- Test ARC on III-V solar cells
- Integrate deposition process into existing cell fabrication at RIT
- Incorporate surface roughness into MATLAB model

References

[1] Guenther, Robert D. *Modern Optics*. 1st ed. New York, Chichester, Brisbane, Toronto, Singapore: JOHN WILEY & SONS, 1990. Print.
[2] "Quantum Efficiency | Pveducation". *Pveducation.org*. N.p., 2017. Web. 23 Apr. 2017.
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[5]"Lecture 23: PV Measurements", *Mycourses.rit.edu*, 2017. [Online]. Available: https://mycourses.rit.edu/d2l/le/content/631740/viewContent/4488407/View. [Accessed: 04- May- 2017]

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