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Modeling of Silicon Solar Cell with Anti-Reflecting Coating

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***Abstract*—**In this study, a silicon solar cell has been modeled and analyzed to enhance its performance by improving the optical properties using an anti-reflecting coating (ARC). The dynamic optical reflectance, transmittance along with the net transmissivity absorptivity product of each layer are assessed as per the diurnal variation of the angle of incidence using MATLAB 2019. The model is tested with various anti-reflective coatings and the performance has also been compared with uncoated cells. ARC improves the optical transmittance of the photon. Higher transmittance of ~96.57% with lowest reflectance of ~ 1.74% at 12.00 hours was obtained with MgF_2 coated silicon cells. The electrical efficiency of the configured solar cell was evaluated for a composite climate of New Delhi, India, for all weather conditions. The annual electricity generation for anti-reflective coated and uncoated crystalline silicon PV Module was observed to be 103.14 KWh and 99.51 KWh, respectively.

***Keywords*—**Anti-reflecting coating, electrical efficiency, reflectance, solar cell, transmittance.

I. INTRODUCTION

SOLAR energy is one of the most promising alternatives to conventional energy sources for electrical energy production via solar cell devices and modules. A solar cell is basically a p-n junction device. The cell is made up of materials having p type and n type semiconducting properties and works on the principle of photovoltaic effect [1]. The solar cell technology produces electricity without polluting the environment and save the fossil fuels. However, high efficiency and low-cost production are the challenges of this technology. Occurrence of reflection losses is one of the prime causes of low efficiency [2]. Solar cell on sun exposure converts only few extents of transmitted solar radiation into the electrical energy. Some of the incident solar energy reflects back from the front surface of cell. In order to enhance the performance of cell, some specific structures have been incorporated in cell for trapping the light in to the material to attain high absorption [3]-[5]. The reflection losses are reduced widely via antireflecting material's coatings over the silicon surface [6]-[9]. Several antireflecting material coatings such as SiO_2, Al_2O_3, ZnS and TiO_2 etc. have been studied experimentally to examine their influence on cell's performance. Numerical investigations on ARC were also carried by many researchers [10], [11]. However, constant optical parameters i.e., transmittivity, absorptivity and reflectivity were taken into account. Here, a silicon solar cell is modeled and examined theoretically for various ARCs with a thickness of one quarter of the project wavelength. A model is developed in MATLAB (2019b) considering varying optical coefficient for each layer as a function of diurnal variation of angle of incidence. Each layer of solar cell is studied for hourly optical transmittance, reflectance and absorption. Electrical efficiency of cell coated with ARC is calculated using developed model.

II. THEORY

The zero reflection or minimization of reflectance is governed by the phenomena of interference of light in thin film, which involve path difference and dependency of the reflectivity on refractive index. The interference mechanism in a thin film is presented in Fig. 1. Reflection can be fully vanished if the reflected rays from the first and second interface are in the antiphase (180° relative phase shift).

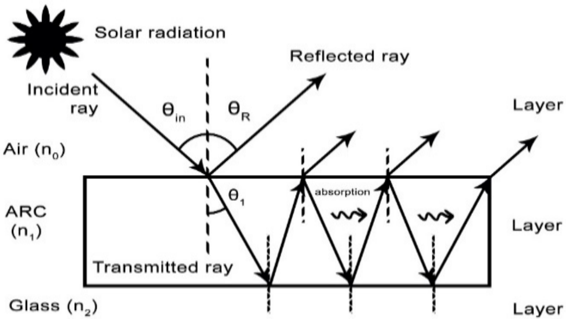

Fig. 1 Phenomenon of interference

For least reflectance, the optimum width and refractive index of ARC should be considered as [12]:

$$n_1 d_1 = \frac{\lambda_0}{4} \tag{1}$$

The expression for calculation of reflected energy from ARC coated semitransparent silicon PV module is given by [13]:

$$R_1 = \frac{r_1^2 + r_2^2 + 2r_1 r_2 cos2\theta}{1 + r_1^2 r_2^2 + 2r_1 r_2 cos2\theta} \tag{2}$$

The transmittivity due to absorption $\left(\tau_{aj}\right)$ and transmittance $\left(\tau_{rj}\right)$ due to refraction are estimated as [14]:

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$$\tau_{aj} = e^{-\frac{\alpha_j \times d_j}{\cos\theta_j}} \tag{3}$$

$$\tau_{rj} = \frac{1}{2}\left(\tau'_{rj} + \tau''_{rj}\right) \tag{4}$$

Further, the total transmittance τ_j is calculated using following expression [14]:

$$\tau_j = \tau_{rj} \times \tau_{aj} \tag{5}$$

In order to calculate the generated electrical energy including thermal losses, the energy balance equation for semitransparent c-silicon solar PV module is given by [15]:

$$\alpha_c \tau \beta_c I(t) = U_T(T_c - T_a) + U_B\,(T_c - T_a) + \eta_c \tau \beta_c I(t) \tag{6}$$

where, the overall transmissivity (τ), top loss coefficient (U_T) and bottom loss co-efficient (U_B) are calculated as:

$$\tau = \tau_{ARC\,\times}\tau_g \times \tau_{EVA} \tag{7}$$

$$U_T = \left(\frac{L_g}{K_g} + \frac{1}{h_0}\right)^{-1} \tag{8}$$

$$U_B = \left(\frac{L_g}{K_g} + \frac{1}{h_i}\right)^{-1} \tag{9}$$

Temperature dependent solar cell efficiency is calculated using following expression [16]:

$$\eta_c = \eta_0[1 - \beta_0(T_c - T_0)] \tag{10}$$

Further, the PV module efficiency is estimated as:

$$\eta_m = \frac{P_0}{P_{in}} = \frac{\eta_c \beta_c \tau I(t)}{I(t)} = \eta_c \beta_c \tau \tag{11}$$

Total monthly electricity is calculated by algebraic sum of electrical energy production from type-a, type-b, type-c and type-d weather conditions of respective month [15]:

$$E_{MT} = E_{Ma} + E_{Mb} + E_{Mc} + E_{Md} \tag{12}$$

The expression for annual electrical energy in KWh is calculated as:

$$E_A = \sum_{i=1}^{12} E_{MT} \tag{13}$$

III. RESULT AND DISCUSSION

Numerical study has been conducted with solar insolation, ambient temperature, and solar cell specification as the input parameters for the model; corresponding outputs are optical coefficients, solar cell efficiency and solar cell temperature. Solar insolation on an inclined surface has been estimated using the solar insolation data on horizontal surface obtained from Indian Meteorology Department (IMD) Pune, India.

Optical coefficients for a typical day in March have been computed using optical model, variation of optical coefficients with hour of the day are shown in Fig. 2.

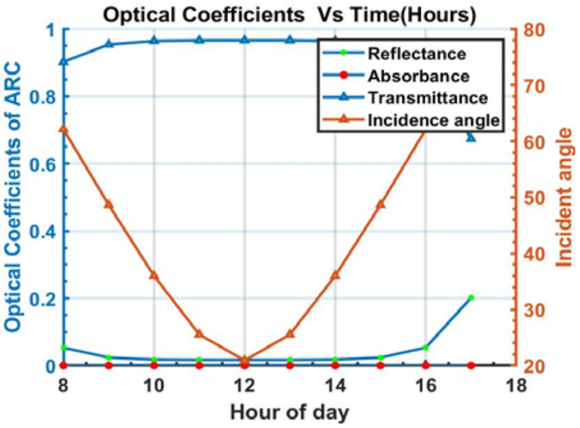

Fig. 2 Hourly variation of optical coefficients

It is evident from Fig. 2 that the optical coefficients are nearly constant between 10:00 hours to 13.00 hours. However, there is significant variation in reflectance and transmittance after 13:00 hours. If these dynamic variations are overlooked by taking the constant values of reflectance and transmittance, one will overestimate the electrical production from the photovoltaic device. Hence it is important to study the photovoltaic device with dynamic optical coefficients.

The diurnal variation of reflectance and transmittance for various coatings given in Table I have also been obtained.

TABLE I
LIST OF VARIOUS COATINGS UNDER INVESTIGATION

S. No.	Coating	Refractive index
1	ARC1 (MgF_2)	1.30
2	ARC2 (SiO_2)	1.46
3	ARC3 (MgO)	1.74
4	ARC4 (Al_2O_3)	1.80
5	ARC5 (Si_3N_4)	1.90
6	ARC6 (TiO_2)	2.30

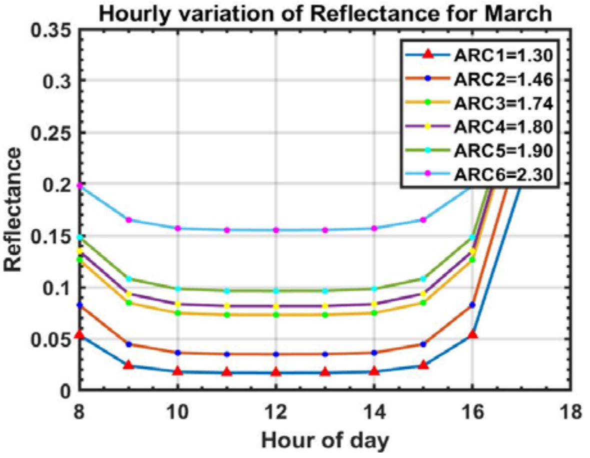

Fig. 3 Hourly variation of reflectance for various anti-reflective coatings

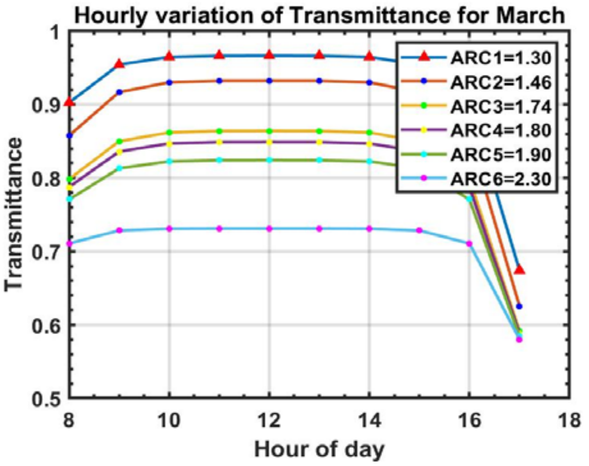

Fig. 4 Hourly variation of transmittance for various anti-reflective coatings

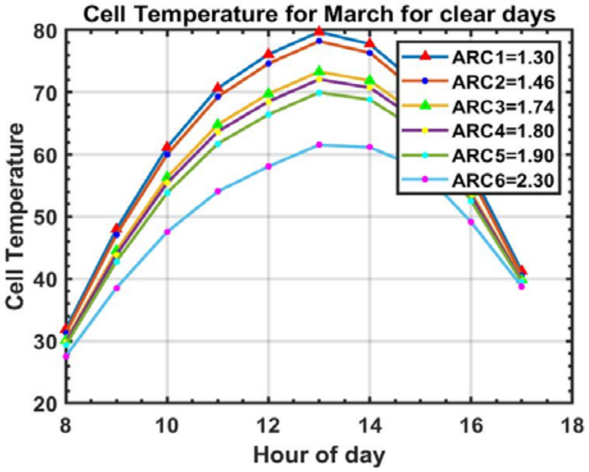

Fig. 5 Diurnal variation of solar cell temperature for various anti reflective coating

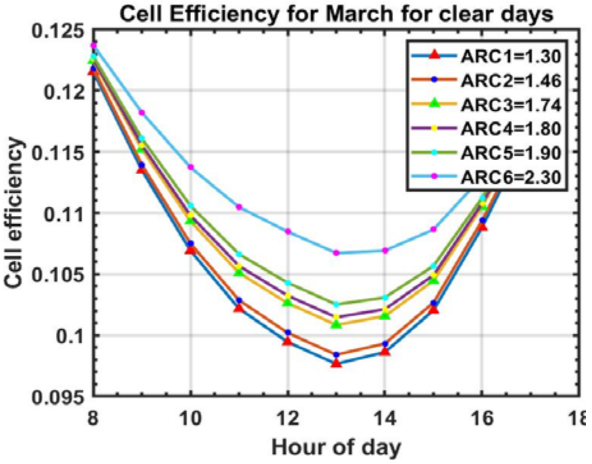

Fig. 6 Diurnal variation of solar cell efficiency for various anti reflective coating

The variations for reflectance and transmittance are shown in Figs. 3 and 4, respectively. Amongst the investigated anti-reflective coatings, MgF_2 partakes minimum reflectance (~1.74%) and maximum transmittance (~96.57). However, the maximum reflectance of ~15.88% and corresponding transmittance of ~73.13% is obtained for TiO_2.

The solar cell temperature and respective solar cell efficiency with various anti reflective coating have been computed for all types of weather conditions (clear day, hazy day, hazy and sunny day and cloudy days) of a given month. The hourly variation of solar cell temperature and solar cell efficiency for typical clear day of March month is presented in Figs. 5 and 6.

From Figs. 5 and 6, it is observed that the higher solar cell temperature is achieved for MgF_2 anti reflective coating due to its lower reflectance. The higher solar cell temperature deteriorates the solar cell efficiency by reducing the flow of charge carrier through the device, hence MgF_2 coating gives lower solar cell efficiency. Solar cell coated with TiO_2 has highest reflectance, hence the solar cell temperature for this ARC is smaller as compared to the other anti-reflective coatings. Hence TiO_2 coated solar cell gives higher values of solar cell efficiency.

To observe the effect of coating on the solar cell, the solar cell temperatures and solar cell efficiencies of anti-reflective coated and without coated solar cell have also been compared and shown in Fig. 7.

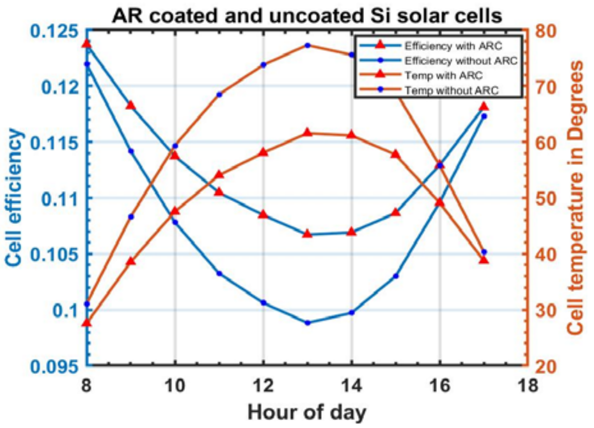

Fig. 7 Diurnal variation of solar cell efficiency for uncoated and coated solar cell

In Fig. 7, a solar cell coated with TiO_2 has been compared with an uncoated solar cell. The anti-reflective coating significantly reduces the temperature by 15.8℃. The corresponding increase in solar cell efficiency is observed to be 0.79%.

The annual electrical energy production for coated and uncoated solar cell has been estimated using (12) and (13). Electrical energy production from uncoated and coated solar cell for each month is depicted in Fig. 8.

It is observed from Fig. 8 that the maximum electrical energy production is obtained for May for both coated and uncoated solar cells. The annual electrical energy production from coated and uncoated solar cell is 103.14 kWh/m^2 and 99.51 kWh/m^2 respectively.

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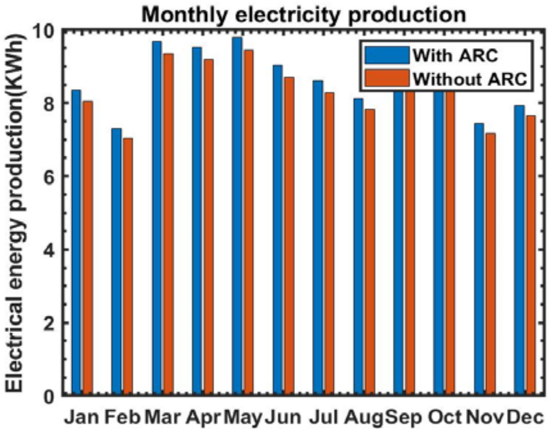

Fig. 8 Monthly electrical energy production from uncoated and coated solar cell

IV. CONCLUSIONS

To reduce the reflection losses in solar cells, silicon solar cell has been modeled with incorporation of ARC and their influence on electrical efficiency is studied. The photovoltaic module, made up of AR coated solar cells demonstrated high efficiency and produced more annual electrical energy than that of uncoated PV module. Using present model, any advanced material coating can be evaluated for its antireflection characteristics, which will help to design an efficient solar cell.

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