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Optical Properties of CaF_2 Thin Film Deposited on Borosilicate Glass and Its Electrical Performance in PV Module Applications

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Featured Application: Minimization of reflection losses in conventional and light weight PV modules.

Abstract: Calcium fluoride (CaF_2) is deposited via vacuum thermal evaporation on borosilicate glass to produce an anti-reflection coating for use in solar modules. Macleod's essential simulation is used to optimize the thickness of the CaF_2 coating on the glass. Experimentally, a 120 ± 4 nm-thin CaF_2 film on glass shows an average increase of ~4% in transmittance and a decrease of ~3.2% in reflectance, respectively, when compared to that of uncoated glass (Un CG), within the wavelength spectrum of approximately 350 to 1100 nm. The electrical PV performance of CaF_2 -coated glass (CaF_2 -CG) was analyzed for conventional and lightweight photovoltaic module applications. An improvement in the short-circuit current (J_{sc}) from 38.13 to 39.07 mA/cm^2 and an increase of 2.40% in the efficiency (η) was obtained when CaF_2 -CG glass was used instead of Un CG in a conventional module. Furthermore, J_{sc} enhancement from 35.63 to 36.44 mA/cm^2 and η improvement of 2.32% was observed when a very thin CaF_2 -CG was placed between the polymethyl methacrylate (PMMA) and solar cell in a lightweight module.

Keywords: high efficiency; reflection; transmittance; anti-reflection coating; calcium fluoride; conventional PV module; light weight PV module; statistical analysis

1. Introduction

A typical photovoltaic (PV) module can be classified as a conventional or light weight module. In a conventional module, glass is used as a top cover and accounts for approximately 70% of the module weight. On the contrary, in lightweight c-Si PV modules, glass is replaced by acrylic (poly methyl methacrylate: PMMA) or other polymers [1–3] to enable such modules to be used in applications where the light weight of the PV module must be limited. Reflection losses are one of the major issues that decrease the effective efficiency of PV modules. A reflection loss of approximately 8% occurs at the front surface of the glass and PMMA because their higher refractive indexes are higher than that of air [4]. This issue can be resolved by using an anti-reflection coating (ARC) material with an ultra-low refractive index (much lower than that of glass) on the front surface of glass. The use of ARC has already been recognized as crucial for various optical and PV panel applications [5,6]. A simple and cost-effective ARC comprises a single layer coating of a material with a refractive index suitable for the desired wavelength spectrum [7]. In this context, optical coatings of fluoride and oxide materials have

been investigated widely owing to their higher band gap. Optical coatings have been widely used in the areas of optoelectronics [8], optics [9], and PV modules [10].

Recently, magnesium fluoride (MgF_2) has gained much attention as an ARC suitable for application on the front cover of PV modules, owing to its low refractive index ($n = 1.37$ at 600 nm); however, it was proven to be less durable in outdoor environments [11]. CaF_2 belongs to a similar category of materials and has been widely investigated by the optics community [12], owing to its lower refractive index (1.43 at 600 nm), when compared to that of glass substrates. It also has a broad transmittance spectrum from 130 to 10,000 nm [13]. Furthermore, it exhibits less solubility in water when compared to MgF_2 [14], which can be a significant factor in view of the chemical resistance towards environmental conditions. Furthermore, it is also used as an ARC in outdoor conditions, optical applications, IR imaging system, and photolithography systems [15]. Therefore, the application of CaF_2 as an ARC for PV modules has been explored in this work. It is important to note that the excellent surface uniformity of ARC is highly dependent on the deposition technique. Numerous techniques have been introduced for depositing CaF_2 thin films on substrates for various purposes such as electron beam evaporation [16–19], radio frequency magnetron sputtering [20], molecular beam epitaxial [21], pulsed laser deposition [22,23] and thermionic vacuum arc [24]. Of these techniques, thermal evaporation has been found to be the most suitable because of its advantages of large-area deposition, low-temperature, and simple process, and it has been proven to be a cheap fabrication process [25].

In this work, a CaF_2 coating was deposited by vacuum thermal evaporation on borosilicate glass (BSG). In this process, the substrates were tilted and rotated at constant speed, resulting in the uniform deposition of the material. The thickness of the ARC was first optimized using the Essential Macleod simulation tool. The optical properties of the thermally evaporated CaF_2 on the glass substrate were investigated using ultraviolet–visible spectroscopy. The electrical performance of the solar cell (SC) was compared by replacing the uncoated glass (Un CG), with CaF_2 -coated glass (CG) in a conventional PV module and placing a thin CaF_2 -CG between the PMMA and SC in the light weight PV module.

2. Materials and Methods

An SC with an active area of $\sim 2.5 \times 2.8 \text{ cm}^2$ was used as a reference SC. The BSG and PMMA sheets were cut according to the active area of the SC. First, the substrates were cleaned sequentially with acetone, isopropyl alcohol (IPA) and deionized water (DIW) for 10 min each in an ultra-sonic bath. The BSG substrates were dried by blowing N_2 gas and then heated on a hot plate at $\sim 100^\circ\text{C}$ for 20 min to remove moisture. The cleaned BSG substrates were loaded immediately into the vacuum thermal evaporation chamber to deposit the thin CaF_2 as the ARC. The deposition was performed at $\sim 110 \text{ A}$ current and under a pressure of $\sim 10^{-6}$ torr. The thickness of the CaF_2 coating on the glass was measured by nano-view Spectroscopic Ellipsometer MF-1000 which was $120 \pm 4 \text{ nm}$. The PMMA was cleaned using soapy water and dried by blowing N_2 gas. Finally, the electrical parameters such as the short circuit current (J_{sc}) and efficiency (η) were characterized by a light-current-voltage (LIV) measurement system under Air Mass 1.5 G 1 sun illumination conditions (100 mW/cm^2). The potential was swept from short circuit condition towards open circuit. The step voltage and delay time were 10 mV and 1 ms, respectively.

3. Results and Discussions

3.1. Structure Characterization

The morphology of the thin film was observed using field-emission scanning electron microscopy (FE-SEM; JEOL JSM-7600F). The cross-sectional FE-SEM image of the CaF_2 film on glass are clearly shown in Figure 1a. The image showed the information about the ARC thickness, its uniformity and the interaction between the coating and substrate. X-ray diffraction (XRD) patterns were recorded in

a 2θ range of 20–70 degrees using an X-ray diffractometer (Bruker, D8 Advance, Turbo X-ray source 18 KW). The typical XRD pattern for the CaF_2 thin film on glass are presented in Figure 1b. It shows that the CaF_2 film is polycrystalline and has a strongest peak of 111, which is in good agreement with the Bannon and Coogan result [26]. The subsequent diffraction lines at 49.6 and 55.6 were identified as 220 and 311 reflexes of the CaF_2 phase, respectively [27].

Figure 1. (a) Cross sectional FE-SEM image of CaF_2 thin film; (b) XRD pattern for the CaF_2 film.

3.2. Optical Characterization

The optical characteristics of the CaF_2 -CG were studied in the wavelength range of ~350 to 1100 nm. By varying the thickness of the coating material, the optical properties of the thin film deposited on the substrate can be changed [28]. The prototype of the Macleod simulation parameters are shown in the Supporting Document.

3.2.1. Reflectance, Transmittance and Absorbance

The transmittance and absorbance of the Un CG and CaF_2 -CG were measured using an ultraviolet-visible spectrophotometer (SCINCO S-3100). The reflectance can be calculated using the relation:

$$R(\lambda) = 100 - T(\lambda) - A(\lambda) \quad (1)$$

where T is the transmittance, and A is the absorbance at λ wavelength.

The spectral behaviors of transmittance and reflectance of the Un CG and CaF_2 -CG, obtained through simulations and experiments, are compared in Figure 2. The Un CG shows an average transmittance and reflectance of ~91% and 8.1%, respectively, across the wide spectrum from ~350 to 1100 nm (Figure 2a), whereas CaF_2 -CG shows improved transmittance and reflectance of ~95.7% and 4.3%, respectively, in the broad spectrum of ~350–1100 nm as shown in Figure 2b. The observed results are in good agreement with the results reported by Hahn et al. [29] and exhibit an improvement in the result, as discussed by Cetin et al. in their study on vacuum-evaporated CaF_2 [24]. The observed absorbance is the minimum (~0.015%) at 600 nm, which is quite low as expected.

3.2.2. Incidence Angle and Refractive Index

The optical characteristics of the PV panel are mainly dependent on the incident angle of light. The influence of different incident angles on the reflectance and transmittance of the CaF_2 -CG computed using Essential Macleod is clearly shown in Figure 3a. The graph shows that the reflectance increases and the transmittance decreases as we go from a low incidence angle to a high incidence angle, and the results are in good agreement with the analysis presented in [30].

Figure 2. Comparison of the simulated and experimentally obtained optical spectra of: (a) the uncoated and (b) the CaF_2 -coated borosilicate glass (BSG).

Figure 3. (a) Influence of the different incident angles on the reflectance and transmittance; (b) refractive index.

The refractive index (n) provides knowledge regarding the local fields, electronic polarization and the phase velocity of light spreading inside a material [25]. The refractive index depends on the deposition technique of coating because the mass density and crystal orientation of the material influences n . The Lorentz–Lorenz equation provides information on the increase in the value of n with the increase in the film density [31]. The dependence of n for the CaF_2 -coated film on BSG over a broad range of wavelength is shown in Figure 3b. We used the Cauchy model for fitting the data from the VB-250 VASE ellipsometer for determining the n value of the produced CaF_2 thin film. The measured refractive index of ~ 1.39 at 600 nm indicated the excellent transparency of $\sim 95\%$ of CaF_2 -CG. There was good improvement in the refractive index, as a result of the vacuum thermal evaporation process, when compared to that presented in the literature and that of bulk material [24].

3.3. Electrical Characterization

As a result of the improvement in the optical characteristics of CaF_2 -CG, a similar improvement was expected in the electrical parameters when the CaF_2 -CG was placed on a pristine SC.

3.3.1. Conventional Module

The performance of the ARC was analyzed by placing the CaF_2 -CG on an SC, as shown in Figure 4. The structure represents the conventional module model in which the Un CG is replaced by the CaF_2 -CG.

Figure 4. CaF₂-coated BSG on solar cell to represent the conventional photovoltaic (PV) module model.

Table 1 shows a comparison of the different PV parameters of the Un CG and CG samples on SC, having average and corresponding standard deviation values. The data were analyzed after recording the performance data of five different samples.

Table 1. Comparison of the different electrical parameters of a solar cell (SC), CaF₂-coated glass (CG)/SC and uncoated glass (Un CG)/SC measured under 1 sun illumination (100 mW/cm²).

Measurement Conditions	V_{oc} (V)	J_{sc} (mA/cm ²)	FF	η (%)	$\Delta\eta$ (%)
SC	0.7072 ± 0.0008	40.58 ± 0.28	0.7406 ± 0.0017	21.25 ± 0.16	0.00
CG/SC	0.7057 ± 0.0007	39.03 ± 0.45	0.7402 ± 0.0020	20.39 ± 0.24	−4.05
Un CG/SC	0.7045 ± 0.0011	38.10 ± 0.43	0.7406 ± 0.0030	19.88 ± 0.24	−6.45

Statistical Analysis

The analysis showed that there is a reasonable improvement being observed in J_{sc} and η as a result of applying ARC on glass. The CG on SC have an average J_{sc} and standard deviation of 39.03 ± 0.45 with an effective η of 20.39 ± 0.24 , respectively, as compared to SC having Un CG with J_{sc} and standard deviation of 38.10 ± 0.43 , with an effective η of 19.88 ± 0.24 , respectively, as shown in Figure 5a. The CG couples, lighter in the device, enhance the J_{sc} and η of the structure [32]. The increase in effective η of 2.40% is observed by increasing the transmittance of ~4% after applying ARC on glass as compared to Un CG. The relation between the current–voltage (J – V) curve for the Un CG and CG on SC, measured under 1 sun illumination (100 mW/cm²) is shown in Figure 5b.

Supporting Documents show the J – V curve for five different PV module structures.

3.3.2. Light Weight Module

The addition of thin glass between the PMMA and SC can help the surface mechanical integrity and the reduce moisture in a light weight PV module. It improves the reliability of module. The performance of the coating in the light weight module model was analyzed by placing the CaF₂-CG between the PMMA and SC. Table 2 shows a comparison of the different PV parameters by placing the Un CG and CG between the PMMA and SC having average and corresponding standard deviation values. The data were analyzed after recording the performance data of five different samples.

Table 2. Comparison of the electrical parameters of a the polymethyl methacrylate (PMMA)/SC, PMMA/CG/SC and PMMA/Un CG/SC measured under 1 sun illumination (100 mW/cm²).

Measurement Conditions	V_{oc} (V)	J_{sc} (mA/cm ²)	FF	η (%)	$\Delta\eta$ (%)
PMMA/SC	0.7089 ± 0.0010	37.80 ± 0.45	0.7603 ± 0.0015	20.37 ± 0.25	0.00
PMMA/CG/SC	0.7082 ± 0.0010	36.43 ± 0.43	0.7612 ± 0.0012	19.64 ± 0.24	−3.58
PMMA/Un CG/SC	0.7074 ± 0.0008	35.65 ± 0.36	0.7601 ± 0.0018	19.17 ± 0.20	−5.90

Figure 5. (a) Statistical analysis of J_{sc} and η on the SC, CG/SC and the Un CG/SC. The graph shows the data from five different cells, which were analyzed with standard deviation values; (b) the J - V characteristics of a SC, CG/SC and Un CG/SC.

Statistical Analysis

The analysis showed that there is a reasonable improvement being observed in J_{sc} and η as a result of putting CG between PMMA and SC. The PMMA/CG/SC have an average J_{sc} and standard deviation of 36.43 ± 0.43 with an effective η of 19.64 ± 0.24 as compared to PMMA/Un CG/SC, which have J_{sc} and a standard deviation of 35.65 ± 0.36 with an effective η of 19.17 ± 0.20 , respectively, as shown in Figure 6a. The relation between the current density–voltage (J - V) curve for the Un CG and CG between the PMMA and SC, measured under 1 sun illumination (100 mW/cm^2), is shown in Figure 6b.

Figure 6. (a) Statistical analysis of J_{sc} and η on the PMMA/SC, PMMA/CG/SC and PMMA/Un CG/SC. The graph shows the data from five different SCs, which were analyzed with standard deviation values; (b) the J - V characteristics of a PMMA/SC, PMMA/CG/SC and PMMA/Un CG/SC.

Supporting Documents show the J - V curve for five different light weight PV module structures.

3.4. Weather-Resistance Test

The brine pollution as a weather resistant test was performed to check the adhesive property of ARC on glass [33]. The coated glass was immersed in a 0.5 M NaCl solution for 30 min. The transmittance of

CG before performing the test was 95.12% while it became 94.95% after the test. The decrease of only 0.18% was seen in transmittance. The results suggested that this ARC has weather-resistant ability.

4. Conclusions

In summary, the optical properties of a CaF_2 as ARC using vacuum thermal evaporation on borosilicate glass substrates are investigated successfully. The optical characteristics of uncoated and CaF_2 -CG were simulated using Macleod simulations and compared experimentally. In addition, the electrical performance of the CaF_2 -CG was analyzed for conventional and light weight module applications. The results showed reasonable improvement in the short circuit current density and module efficiency. The findings suggest that, because of the lower solubility of CaF_2 when compared to that of MgF_2 , the CaF_2 -ARC on glass can be beneficial for improving the electrical performance of solar cell modules, and can be utilized effectively in both types of PV modules (conventional and light weight). The CaF_2 -ARC showed a good weather-resistant ability. Moreover, various treatments like annealing and hexamethyldisilazane on coated surface could be an interesting topic in the future to further improve the optical properties and environmental sustainability of this material on glass.

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