

Conference Paper Antireflective Nanocomposite Based Coating on Crystalline Silicon Solar Cells for Building-Integrated Photovoltaic Systems

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Building-integrated photovoltaic (BIPV) systems represent an interesting, alternative approach for increasing the available area for electricity production and potentially for further reducing the cost of solar electricity. In BIPV systems, the visual impression of a solar module becomes important, including its color. However, the range of solar cell colours and shapes currently on offer to architects and BIPV system designers is still very limited, and this is a barrier to the widespread use of PV modules as a constructional "material." The color of a solar module is determined by the color of the cells in the module, which is given by the antireflection coating (ARC). However, access to efficient, but differently colored, solar cells is important for the further development of BIPV systems. In this paper, we have used Diamond-like nanocomposite layer as an Antireflective Nanocomposite based (ARNAB) coating material for crystalline silicon solar cell, and the impact of varying the color of an ARC upon the optical characteristics and efficiency of a solar cell is investigated. In addition to a comparison of the optical characteristics of such solar cells, the effect of using colored ARCs on solar cell efficiency is quantified using the solar cell modeling tool PC1D.

1. Introduction

Building-integrated photovoltaic system is the combination of aesthetic aspects, carbon-free power generation, and weather protection that makes glass-glass solar modules so attractive on building facades and roofs. Solar facades are an environmental-friendly alternative to granite, marble and other construction materials and create inspirational, functional solutions. It is with good reason that increasing numbers of builders, architects, engineers, and planners advocate this technology.

Moreover, BIPV system represents an interesting, alternative approach for electricity production and potentially for further reduction of the cost of solar electricity [1]. However, overall market share is not at all significant at present. One factor is that BIPV elements are in part hampered by a limited choice of esthetic variation. It has been pointed out by the architectural survey (~85%) that esthetic concerns would allow for the installation of solar energy systems with reduced efficiency [2]. The use of photovoltaic modules in architectural applications is now firmly established, and large modules of glass-glass construction produced specifically for the BIPV market are available. However, the range of solar cell colours and shapes currently on offer to architects and BIPV system designers is still very limited, and this is a barrier to the widespread use of PV modules as a constructional "material." In principle, coloured filters could be used to change the appearance of solar cells or modules. However, this would add complexity and cost to the manufacturing process in addition to preventing a significant portion of the incident radiation from reaching the surface of the cell. A more efficient and cost-effective approach is to use the thin film interference effect in the antireflection coating, which is responsible for the familiar dark blue colour when optimized for minimum reflection under AM1.5. Adjusting the thickness of the antireflection coating enables a range

TABLE 1: Solar cell parameters used during PCID simulation.

| Parameter | Value |
|--|-----------------------------------|
| Bulk silicon material thickness | 200 µm |
| Bulk doping concentration | $10^{16} cc$ |
| Emitter n ⁺ junction depth | $0.3\mu\mathrm{m}$ |
| Diffusion: sheet resistance/peak doping | $45 \Omega/; 1 \times 10^{19} cc$ |
| Rear p ⁺ concentration | $1 \times 10^{19} \text{ cc}$ |
| Bulk carrier lifetime | 1000 µs |
| Surface recombination velocity at emitter and rear surface | 10000 cm/s |



FIGURE 1: (a) Experimental and simulated spectral reflectance along with simulated IQE and EQE of mc-Si solar cell with fed blue colour ARC. (b) Simulated illuminated *I-V* characteristic of fed blue colour mc-Si solar cell.

of colours to be produced, albeit with some loss of energy conversion efficiency.

An initial investigation of the colour and efficiency of Laser Grooved Buried Contact (LGBC) solar cells as a function of the thickness of the LPCVD (Low Pressure Chemical Vapour Deposition) silicon nitride antireflection



FIGURE 2: (a) Experimental and simulated spectral reflectance along with simulated IQE and EQE of mc-Si solar cell with Yellow colour ARC. (b) Simulated illuminated *I-V* characteristic of yellow colour mc-Si solar cell.

coating was reported by Mason et al. [3] in 1995. In the European BIMODE project in the late 1990s, coloured cells fabricated using this technique were used to produce a number of demonstration modules of various shapes, with module efficiencies in the range 6.3% to 12.1% [4]. Subsequent commercialization of coloured cell products has been limited in part by the relatively low manufacturing yield resulting from inadequate process control in the silicon nitride deposition and subsequent process steps, which leads to an unacceptable degree of colour variation both across an individual cell and from cell to cell and batch to batch.

The deposition of silicon nitride single layer antireflection coating using plasma enhanced chemical vapor deposition (PECVD) with a dark blue color is the most commonly used process nowadays in the photovoltaic industry. However, access to efficient, but differently colored, solar cells is important for the further development of BIPV system.



FIGURE 3: (a) Experimental and simulated spectral reflectance along with simulated IQE and EQE of mc-Si solar cell with Magenta colour ARC. (b) Simulated illuminated *I-V* characteristic of magenta colour mc-Si solar cell.

In this paper, we have used Diamond-like nanocomposite layer [5–7] as an Antireflective Nanocomposite Based (ARNAB) coating material for crystalline silicon solar cell, and the impact of varying the color of an ARC upon the optical characteristics and efficiency of a solar cell is investigated. The overall transmittance and reflectance of a set of differently colored single layer ARCs are compared with multilayered ARNAB coating, all made using DLN layer deposition by PACVD technique. In addition to a comparison of the optical characteristics of such solar cells, the effect of using colored ARCs on solar cell efficiency is quantified using the solar cell modeling tool PCID.

2. Experimental

Diamond-like nanocomposite films optimized for an Antireflective Nanocomposite Based (ARNAB) coating were synthesized and characterized in this work. Plasma enhanced



FIGURE 4: (a) Experimental and simulated spectral reflectance along with simulated IQE and EQE of mc-Si solar cell with Blue colour ARC. (b) simulated illuminated *I-V* characteristic of blue colour mc-Si solar cell.

chemical vapor deposition (PECVD) is used for DLN film synthesis [6]. The synthesis procedures attempt to exclude or minimize cluster formation in the sources, in the primary plasma, in the deposition region, and during film growth. The mean free path of each particle species must exceed the distance between its source and the growing film surface. Radicals were formed via glow discharge plasma breakdown of the precursor using a quasi-closed plasmatron, and high frequency (13.56 MHz, 0.3-5.0 kV) fields were used to transport the radicals to the substrate. Variation of precursor, plasma, and field conditions changes the state of the basic matrix. The precursors belong to family of Silazanes, and the species selected depends on the elemental ratios and bonding states desired in the film. Deposition pressure utilized 7.0×10^{-4} torr. The growth rate of DLN films typically varies from 1.0 to $3.0 \,\mu\text{m/hr}$ and depends on a number of factors. The details experimental procedure has already mentioned in the author's published paper [6, 7]. By changing



FIGURE 5: (a) Experimental and simulated spectral reflectance along with simulated IQE and EQE of mc-Si solar cell with Greenish blue colour ARC. (b) simulated illuminated *I-V* characteristic of greenish blue colour mc-Si solar cell.

deposition conditions, the optical properties of DLN film can be varied over a wide range. The substrates used were boron doped NaOH-NaOCl polished multicrystalline silicon (mc-Si) wafers [8].

Prior to the deposition of the films of ARNAB layer, the thickness and deposition rate of the separate films were assessed by precursor flow rate, chamber working pressure and other deposition parameters respectively. The refractive index and thickness of the deposited ARNAB layers for BIPV system were estimated by ellipsometer. In addition to experimental films optical characterization, the impact of the resulting reflection variations upon the solar cell efficiency was determined by device modeling using PC1D software.

3. BIPV Modeling and Experimental Results

The modeling was made by using PC1D simulation software. During modeling, textured p-type crystalline silicon had



FIGURE 6: (a) Experimental and simulated spectral reflectance along with simulated IQE and EQE of mc-Si solar cell with Dark blue colour ARC. (b) Simulated Illuminated *I-V* Characteristic of Dark blue colour mc-Si Solar Cell.

taken. Above the emitter surface, AR coating layer was considered. Simulation study was carried out by varying different coating thickness and refractive index and compared the data with experimentally observed data.

Standard n-p-p⁺ structured solar cell had taken with surface area 100 cm². The Solar cell parameters used during PC1D simulations are described in Table 1.

During simulation, each simulated solar cell reflectance curve was fitting with experimental reflectance curve. After matching the simulated reflectance spectra in each case, the expected solar cell parameters and illuminated current voltage, IQE, and EQE characteristics—were, respectively, drawn as shown in Figures 1, 2, 3, 4, 5, and 6 and Table 2.

It was observed from Table 2 that the dark blue colour AR coated mc-Si solar cell can be able to produce the highest simulated efficiency whereas yellow colour c-Si solar cell can

| Sample | ARC thickness (nm) | ARC r.i* | Broad band reflectance (%) | Isc (A) | Voc (V) | η (%) |
|------------------------|-----------------------|-------------|-------------------------------|---------|---------|-------|
| #120001B (without ARC) | _ | | _ | 2.53 | 0.64 | 13.5 |
| #121006 fed blue | 125 | 1.85 | 7 | 3.10 | 0.66 | 17.02 |
| #121008A yellow | 175 | 1.85 | 1 | 2.99 | 0.65 | 16.03 |
| #121010 magenta | 205 | 1.83 | 2 | 2.92 | 0.65 | 16.09 |
| #120703B blue | 94 | 1.85 | 5 | 3.40 | 0.65 | 18.82 |
| #121006B green blue | 250 | 1.85 | 1.5 | 3.00 | 0.65 | 16.51 |
| #120706B dark blue | 100 | 1.85 | 1.2 | 3.49 | 0.65 | 19.35 |

TABLE 2: Simulated solar cell's parameters after curve fitting with experimental reflectance curve, refractive index, and thickness of ARNAB coating.

ARC: antireflective coating; *r.i: refractive index; η : efficiency.



FIGURE 7: Photographs of colour mc-Si samples fabricated by ARNAB layer deposition using PACVD technique.

give the lowest solar cell simulated efficiency. Other colours mc-Si solar cell (i.e, blue, fed blue, greenish blue and magenta solar cells) efficiencies were in-between deep blue and yellow respectively. Moreover, it was observed that the efficiency of simulated solar cell without AR coating is around 13.5%. Therefore, the lowest efficiency 16.3% with yellow colour was also reasonably high compared with the efficiency of uncoated mc-Si solar cell. Photographs of fabricated colour ARNAB layer coated multicrystalline silicon samples are shown in Figure 7.

In order to investigate the potential of ARNAB layer deposition techniques for fabrication of coloured antireflection coatings, a selection of target colours were made. Optimization with respect to thickness and possible adjustments in target reflectance spectra during simulation may give further improvements in efficiency.

4. Conclusion

We had shown that ARNAB coating on crystalline silicon solar cells can be tailored to give prominent colours while retaining high efficiencies. Five different colours (i.e., fed blue, yellow, Magenta, blue, greenish blue and deep blue) mc-Si wafers were fabricated by using different thickness ARNAB coating. The simulated efficiency of mc-Si solar cells was in the range from 19.35% for standard dark blue ARC to 16.03% for a yellow ARC. Fed blue, magenda, blue, and greenish blue cells all had efficiencies over 16%. This approach represents a very simple AR coating process flow for multicrystalline silicon solar cells and can be viable, short-term route to the production of differently coloured solar cells/modules for use in BIPV systems, and other applications where esthetic concerns are of importance.

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