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A simplified method to modulate colors on industrial multicrystalline silicon solar cells with reduced current losses

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Abstract

This paper investigates the impact of SiO_xN_y/SiN_x:H double layer antireflection (DLAR) coatings on color modulation and cell efficiencies of multicrystalline silicon (mc-Si) solar cells. We presented a three dimensional ellipsoid surface model to simulate the concave-like morphology formed by acidic texturization. Afterwards, reflectivities of these acidic textures coated by DLAR coatings over 300–1100 nm are calculated by Monte Carlo ray tracing method. Simulated results show that DLAR coatings can flexibly modulate the color with reduced current losses compared to single SiN_x:H layer. SiO_xN_y was deposited by electron beam evaporation onto fabricated industrial solar cells to vary their colors. The busbars were sheltered by a mask to prevent the deposition of SiO_xN_y on them. This simplified method avoids adjustment of the standard fabricating process. High agreement between simulated and measured reflectance is achieved. The IV test results of colored solar cells are in good accord with the calculated results, which indicates the effectiveness of DLAR coatings in reducing the current losses.

Keywords: Ellipsoid model; Double layer antireflection coatings; Monte Carlo ray tracing; Colored mc-Si solar cells

1. Introduction

Promoting the use of photovoltaics (PV) in buildings is one of the most important ways of reducing building energy consumption. Building-integrated and building-attached photovoltaics (BIPV and BAPV) have therefore attracted a great deal of research interests (Yoo and Manz, 2011; Yoon et al., 2011; Santos and Rüther, 2012). Two factors are hindering the widespread utilization of BIPV and BAPV: high cost and limited choices of aesthetics. The first factor has become less influential as module price is undergoing a continuously downward trend (Jäger-Waldau, 2012). The second factor is being increasingly critical as PV modules are being more visible in urban area. The mere colors of black and blue of conventional PV modules may easily cause incompatibility with the outer appearance of architectures. Hence PV modules with multiple colors are desirable. One approach is to vary the thickness of the antireflection (AR) coating and as a result a wide range of colors can be obtained. Tobias et al. (1999) reported the colored solar cells with single layer antireflection (SLAR) coating on random pyramid textures, but the drawback was the significant drop in short-circuit current (about 2–3 mA/cm^2 less than optimum short-circuit current). To improve the optical performance, multilayer AR coatings had been studied by simulation and

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experiments (Spiegel et al., 1995; Selj et al., 2011). However, both references only presented the outcomes on polish surface. For pyramid texture surface, we showed that it is possible for colored cells with multilayer AR coatings to achieve equal J_{sc} with standard blue cell (Chen and Yang, 2012). Nevertheless, results on acidic texture for multicrystalline silicon (mc-Si) solar cells are absent. For acidic texture surface, we preliminarily showed that SiO_2/SiN_x:H double layer antireflection (DLAR) coatings can modulate the colors of solar cells (Li et al., 2013). However, since the refractive index of SiO_2 coating is almost identical with that of ethylene vinyl acetate (EVA) sheet, encapsulating the solar cells into module would eliminate the effectiveness of SiO_2 coating, turning the DLAR coatings into SLAR coating. Therefore, material with refractive index higher than SiO_2 needs to be studied to address the issue of encapsulation.

In this paper, we aimed at studying the impact of SiO_xN_y/SiN_x:H DLAR coatings thickness upon the color and efficiency of mc-Si solar cells by numerical simulation and experiments. Typically, concave-like morphology is formed by acidic solutions of HF and HNO_3. Spherical surface model was studied in Nishimoto et al. (1999) and Li et al. (2012), however, the assumption that the spherical surface is ideally smooth is not precise, because the surface is partially Lambertian. We therefore developed a three dimensional (3D) ellipsoid model to simulate the acidic textures of mc-Si wafers to include Lambertian reflectance. Monte Carlo ray tracing algorithm (Brendel, 1995; Brendel and Scholten, 1999) was adopted for the calculation of the reflectivity and absorptivity to yield colors and J_{sc}. On experiments, $156 \times 156\ mm^2$ industrial mc-Si solar cells were fabricated with SiN_x:H SLAR coating. Then $SiO_xN_y(n = 1.8)$ was deposited by the use of electron beam (e-beam) evaporation technique onto the solar cells to form SiO_xN_y/SiN_x:H DLAR coatings. To prevent the deposition of SiO_xN_y onto the busbars from forming a dielectric layer and thus affecting the subsequent cell testing and soldering process, a mask was used to shelter the busbars. Therefore, only one additional step is necessary for colored cells fabrication. No additional requirement to match the front metallization process with the AR coating thicknesses is needed. Semi-sphere reflectance and *I–V* measurements were performed for comparison and analysis, showing that the DLAR coatings could effectively reduce current losses.

2. Optical simulation

2.1. Geometrical model

The typical acidic texturing of mc-Si wafer is formed by etching the surface defects caused by saw damage. The formed surface morphology is concave-like pits, as shown in Fig. 1(a). To symbolize the surface, we chose a 3D ellipsoid surface model which is illustrated in Fig. 1(b), as the unit cell for the concave-like texture.

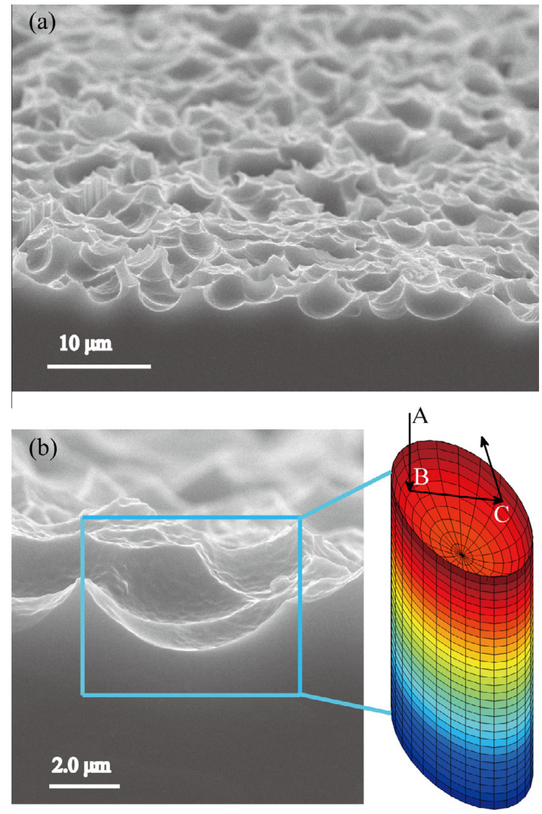

Fig. 1. Scanning electron microscope photographs showing the cross section of acidic textured mc-Si wafers (a) and 3D ellipsoid surface model symbolizing one unit pit of on the wafer surface (b).

The geometry of the ellipsoid surface can be defined by the following equation:

$$\frac{x^2}{r_1^2} + \frac{y^2}{r_2^2} + \frac{z^2}{r_3^2} - 1 = 0, \quad (z < 0) \tag{1}$$

where r_1, r_2, r_3 are the geometric parameters for the ellipsoid surface.

As shown in Fig. 1(b), point A with its coordinate (x_0, y_0, z_0) randomly generated is the starting point of incident ray $\overrightarrow{AB}$, while point $B(x_i, y_i, z_i)$ is the point at which ray $\overrightarrow{AB}$ hitted the textured surface. The unit vector of $\overrightarrow{AB}$ is noted as (x_d, y_d, z_d) which represents the direction of $\overrightarrow{AB}$. For normal incident ray, $\overrightarrow{AB} = (0, 0, -1)$. The parametric equation of is defined as follows:

$$\begin{aligned} x &= x_0 + x_d \cdot t \\ y &= y_0 + y_d \cdot t \\ z &= z_0 + y_d \cdot t \end{aligned} \tag{2}$$

where $t > 0$ indicates that A is the starting point.

By substituting Eq. (2) into Eq. (1), one can obtain

$$at^2 + bt + c = 0 \tag{3}$$

where