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Light management in hydrogenated amorphous silicon germanium solar cells



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ABSTRACT

A finite difference time-domain (FDTD) simulation and experimental investigation of the enhanced light absorption in superstrate (PIN) type amorphous silicon germanium solar cells (a-SiGe:H) deposited on wet-etched Aluminum-doped zinc oxide (ZnO:Al) substrates are presented. Depending on the etching times, optimal vertical and lateral surface feature sizes, which balance the light scattering intensity and the light scattering angle, exist for a-SiGe:H solar cells. The surface morphology analysis, FDTD simulation, and experimental results concurrently show the maximum absorption of the long wavelength region will be achieved when the randomly textured surface with proper vertical and lateral surface feature sizes is applied in the solar cells. Due to the small inclination angle of 5°–20° on the wet-etched ZnO:Al surfaces, the light absorption is enhanced without producing a negative effect on the open circuit voltage (V_{oc}) and fill factor (FF) of the a-SiGe:H solar cell, unlike the negative effects seen in hydrogenated microcrystalline silicon solar cell ($\mu\text{-Si:H}$) on low-pressure chemical vapor deposition (LPCVD) ZnO substrates. An initial efficiency of 10.10% for PIN type a-SiGe:H single junction solar cell was achieved by adopting the optimized surface morphology.

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1. Introduction

The combination of optimized electrical device physics and maximized effective optical absorption is necessary to improve the solar cell efficiency. However, the electrical properties rely heavily on the chosen material system. For example, the electrical properties of hydrogenated amorphous silicon germanium (a-SiGe:H), which is widely used as a low band gap material for multi-junction solar cells because of its tunable optical characteristics, deteriorate with germanium alloying [1–3], which aims to achieve higher long wavelength response needed in multi-junction solar cells. The defect density, Urbach energy, microstructure factor [4,5] and the resulting internal electric field distortion and hole transport capacity [6,7] cause the open circuit voltage (V_{oc}) and fill factor (FF) of the a-SiGe:H solar cell to decrease and increase the light degradation [8]. In addition to the effort for improving the material quality, in the last few years, novel structural designs [9–11] of low band gap (1.4 eV) a-SiGe:H solar cells have been proposed by optimizing the internal field profiles to mitigate the need for high quality materials. Nevertheless, inherent

material limitations impose restrictions on additional efficiency improvement.

In recent years, light management concepts have been applied to thin film solar cells [12–16], which enormously improves the performance. Although hydrogenated amorphous silicon (a-Si:H) solar cells focus on the light coupling of the short wavelength light, the introduction of the light trapping concepts successfully reduces the electric thickness of cells' intrinsic layers, which then improves the light stability [12]. The short circuit current density (J_{sc}) of hydrogenated microcrystalline silicon solar cell ($\mu\text{-Si:H}$) has been elevated to $> 30 \text{ mA/cm}^2$ by integrating optimized light management techniques [17]. Although the a-SiGe:H solar cells in this study will be employed as middle sub-cells in triple junction solar cells, the a-SiGe:H solar cells experience more serious light-induced instability resulting from the germanium incorporation in comparison to a-Si:H. Therefore, a-SiGe:H solar cells require the efficient use of light trapping techniques to reduce demands from the thickness of the intrinsic layers and the germanium content. Furthermore, owing to the top cell, which serves as a blue filter, and no benefits from the back reflector for the existence of the bottom cell, it's difficult to match the current of the a-SiGe:H middle cell to the current of the top and bottom cells. Therefore, the absorption in the 500–900 nm range for the a-SiGe:H cell is

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essential for improving the performance of the a-Si:H/a-SiGe:H/ $\mu\text{c-Si:H}$ triple junction solar cell. As a result, light trapping designs are very important. The NIP type a-SiGe:H solar cells first adopt highly reflective back reflectors (BRs) and optimized BRs with high scattering capacity. At the same time, the innovative dual function nc-SiO_x:H layer has been used as an intermediate reflective layer for the a-SiGe:H middle cell in the a-Si:H/a-SiGe:H/nc-Si:H multi-junction solar cell, leading to a world record initial efficiency of 16.3% [18]. Because of the reflection loss from the glass in PIN type a-SiGe:H solar cells, it is more urgent to develop light trapping techniques compared to the NIP type solar cells. While much work has been done to improve the electrical properties of a-SiGe:H solar cells [19–21], little research has been done on the light management of PIN type a-SiGe:H solar cells.

For maximizing the optical benefits and mitigating the material systems dependency, light management provides a new way for further improving PIN type a-SiGe:H solar cells. Light trapping plays an important role in elevating the optical absorption. The goal of the light trapping is the enlargement of the photon path across the absorbing layer, thus increasing the probability of incoming photon absorption. This leads to thinner electrical thickness and thicker optical thickness of a-SiGe:H materials. To increase the optical absorption in the intrinsic layer, different light trapping techniques have been applied, such as photonic crystals [22–25], dielectric gratings [26,27], highly reflective back contacts [28–30], plasmonic nanoparticles [31,32], and randomly textured surfaces [33–36]. Randomly textured surfaces have been widely used from a practical perspective. Because of the contributions of surface features with different vertical and lateral sizes, the light coupling and trapping can be improved over a broad spectrum range.

For applications in multi-junction solar cells and for mitigating the need for a-SiGe:H materials with a high germanium content, we need to maximize the response in the long wavelength region of 600–900 nm in a-SiGe:H solar cells. The light scattering properties are closely related to the surface morphology, which can be characterized by typical vertical and lateral features, i.e., the RMS roughness σ_{rms} and the correlation length l_c . These two statistical parameters describe the phase delay and the direction of light scattering [37], thus the scattering distribution in the forward direction (transmission) is determinate. The response spectrum range and intensity can be modulated by surface morphology with proper (σ_{rms} , l_c) values.

In this study, we first conduct a surface morphology analysis of the wet-etched ZnO:Al with different etching times and evaluate the light scattering properties of the corresponding morphologies. For verifying the light enhancement effect, we rigorously analyze the absorption enhancement in a complete a-SiGe:H single junction solar cell using finite difference time-domain (FDTD) simulation by taking the real substrate profile into account. Based on the simulation results, we aim to correlate the surface morphology, light scattering behavior, and resulting light absorption in a-SiGe:H solar cells and provide a guideline for maximizing the long wavelength response. We then apply the wet-etched ZnO:Al in fabricated a-SiGe:H solar cell and evaluate the optical and electrical effect of the substrates on the cells. The light path enhancement factor is also presented for illustrating the light trapping effect. Finally, the optimized wet-etched ZnO:Al was applied in the deposition of a a-SiGe:H single junction solar cell with a good photo-electrical structure.

2. Experiment

Using radio frequency (RF) magnetron sputtering, 1.1- μm -thick sputtering ZnO:Al films were deposited on Eagle XG substrates. The films utilized in this study show outstanding electrical and

optical properties, such as resistivity as low as $4.94 \times 10^{-4} \Omega \text{ cm}$ and an average total transmittance greater than 85% from 400 nm to 1100 nm.

The ZnO:Al films were chemically wet-etched in a 0.5% HCl solution with different etching times from 0 s to 50 s to obtain the rough surfaces with different vertical and lateral features (σ_{rms} , l_c). The surface topographies of the samples are determined from atomic force microscope (AFM) measurements over a scanning area of $10 \mu\text{m} \times 10 \mu\text{m}$. Then, the surface topographies are statistically analyzed, and the absorption power profiles are rigorously solved to verify suitable vertical and lateral features (σ_{rms} , l_c).

For representing the optical scattering properties of the textured ZnO:Al films, the total optical transmission $T_t(\lambda)$ and specular transmission $T_s(\lambda)$ of the textured ZnO:Al films were measured in air with ultraviolet–visible–near infrared (UV–VIS–NIR) spectrophotometry. Then, the transmission haze spectrum was calculated.

After that, the textured ZnO:Al films are introduced into the a-SiGe:H solar cell structure as a transparent conductive oxide (TCO) to determine the most suitable rough surface with proper (σ_{rms} , l_c) on which the a-SiGe:H solar cell shows a maximum long-wavelength response. The a-SiGe:H solar cells studied in this work were deposited by radio frequency plasma enhanced chemical vapor deposition (RF-PECVD) on ZnO:Al front TCO with different etching times. A mixture of Si₂H₆, H₂, and GeH₄ are used as source gases for preparing the intrinsic layer of the a-SiGe:H cells. The final structure of the a-SiGe:H solar cell is Glass/ZnO:Al/(p)nc-Si:H/buffer/(graded)a-SiGe:H/buffer/(n) $\mu\text{c-Si:H}$ /BR(PIN type). The active area is 0.253 cm², and the thickness of the absorber layer is around 150 nm.

The current–voltage characteristics were measured in the dark and under 1-sun (AM 1.5, 25 °C, 100 mW/cm²). By fitting the illuminated J - V curves with the uniform field model [38], we obtained the hole mobility–lifetime product $\mu\tau_p$ to characterize the quality of the intrinsic layer [39]. To characterize the optical and electrical behavior of the solar cells, the external quantum efficiency (EQE) under 0 V and -1 V [40] were measured in the 300 nm to 900 nm range. We calculated J_{sc} above 530 nm by integrating EQE(λ) in this region to illustrate the long wavelength response strength. The total reflection $R(\lambda)$ in the 300 nm to 900 nm wavelength range was measured from the substrate side of the solar cells using UV–VIS–NIR spectrometry, and the light enhancement factor is calculated using the method proposed by Berginski [41].

In addition to the optical benefits from the textured substrates, we should also consider any negative effects on the electrical properties of the solar cells resulting from the texture-induced large cracks [42]. The cracks always occur in the valleys with the steepest slopes. In order to evaluate whether the optical enhancement occurs at the expense of the texture-induced electrical deterioration, we evaluate the histogram of the integral inclination angles of the surface by calculating the angle between the gradient vector and the vector perpendicular to its projection surface for each data point in the AFM matrix. This histogram is used to illustrate the angle above which the steepest slopes exist [43].

3. Results and discussions

3.1. Surface morphology

Fig. 1 shows the $10 \mu\text{m} \times 10 \mu\text{m}$ AFM scans of ZnO:Al films with different etching times. Because the solar cells are deposited on the ZnO:Al TCOs, Fig. 1 shows the surface morphologies of the TCOs before solar cell deposition.

Without etching, the ZnO:Al film has a nearly flat surface, but crater-like features appear on the ZnO:Al films after being etched.

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