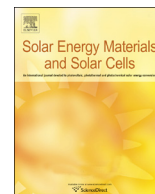




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Remarkable progress in thin-film silicon solar cells using high-efficiency triple-junction technology

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ABSTRACT

Despite the many advantages of thin-film silicon (Si) solar cells, their low efficiencies remain a challenge that must be overcome. Efficient light utilization across the solar spectrum is required to achieve efficiencies over 15%, allowing them to be competitive with other solar cell technologies. To produce high-efficiency thin-film Si solar cells, we have developed triple-junction solar cell structures to enhance solar spectrum utilization. To maximize the light management, in-house ZnO:Al layers with high haze ratios and high transmittances were developed. In addition, novel doping layers, such as n-type microcrystalline silicon oxide ($\mu\text{c-SiO}_x\text{:H}$), which has a very low refractive index, and p-type microcrystalline silicon oxide ($\mu\text{c-SiO}_x\text{:H}$), which has a wide bandgap, were successfully applied to the optical reflector and the window layer, respectively. Thin-film quality control techniques for the deposition of hydrogenated amorphous silicon (a-Si:H) in the top cell, hydrogenated amorphous silicon-germanium (a-SiGe:H) or hydrogenated microcrystalline silicon ($\mu\text{c-Si:H}$) in the middle cell, and hydrogenated microcrystalline silicon ($\mu\text{c-Si:H}$) in the bottom cell were also important factors leading to the production of high-efficiency triple-junction solar cells. As a result of this work, an initial efficiency of 16.1% (in-house measurement) in the a-Si:H/a-SiGe:H/ $\mu\text{c-Si:H}$ stack and a stabilized efficiency of 13.4% (confirmed by NREL) in the a-Si:H/ $\mu\text{c-Si:H}$ / $\mu\text{c-Si:H}$ stack were successfully achieved in a small-area triple-junction solar cell with dimensions of 1 cm × 1 cm.

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1. Introduction

The electricity cost for solar power generation continues to decrease as a result of increasing installation of photovoltaic systems and progress in solar cell technology, which affects the manufacturing cost and conversion efficiency for solar cells, respectively. It appears that the recent plunge in the price of solar cells due to an oversupply of photovoltaic modules will make economic parity with the grid possible within 2–3 years, particularly in high-insolation areas. Meanwhile, producers of solar cells must improve solar cell efficiency and reduce manufacturing costs significantly to survive in the challenging current market environment.

Thin-film Si solar cells have received attention due to their potential for large areas and low-cost manufacturing. The abundance of raw materials makes these solar cells more attractive as a renewable energy source compared to other compound semiconductor thin-film solar cells. In addition, these solar cells exhibit a low temperature coefficient, which is especially beneficial in high-insolation areas, including the Sun Belt region. Despite the many advantages of thin-film Si solar cells, their low efficiencies still

present a challenge that must be overcome. The efficiency of a single-junction amorphous Si solar panel is only 6–7%. Oerlikon Solar has demonstrated the possibility of increasing the module efficiency up to 11% by using double-junction technology, including amorphous Si (a-Si:H)/microcrystalline Si ($\mu\text{c-Si:H}$) junctions [1]. However, in our opinion, a module efficiency of 12% is necessary to be competitive with other solar cell technologies. We now believe that conventional a-Si:H/ $\mu\text{c-Si:H}$ double-junction solar cells will eventually be replaced by triple-junction solar cells. Triple-junction solar cells offer an even more efficient utilization of the solar spectrum by incorporating thin component cells in which the intrinsic layer materials have appropriate bandgaps for the successful absorption and collection of blue light in the top cell, green light in the middle cell, and red light in the bottom cell [2].

A conversion efficiency of 16.3% (*init.*) in a thin-film Si solar cell with an n–i–p stacked triple-junction structure (a-Si:H/a-SiGe:H/ $\mu\text{c-Si:H}$) was recently reported by United Solar [3], suggesting a possible approach for exceeding the current, inadequate efficiency limit for thin-film Si solar cells. In this article, we are hoping to offer another possibility for achieving such a high efficiency by creating a p–i–n stacked triple-junction thin-film Si solar cell. Our recent progress into developing element technologies for this triple-junction solar cell and the integration technologies for the triple-junction stack will be described in detail in the sections that follow.

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2. Element technologies for a high efficiency triple-junction solar cell

2.1. Transparent conductive oxide (TCO) as a front contact layer

The efficiency of a superstrate-type thin-film Si solar cell strongly depends on the quality of the textured TCO layer used for the front electrode material. To improve cell efficiency, it is necessary to prepare a TCO layer with a high transparency in the solar spectrum and to optimize the surface morphology for light scattering by controlling the deposition and texturing conditions. In our work, we have developed a textured ZnO:Al layer with the following characteristics: a high transparency; a high haze ratio, particularly at long wavelengths (700 nm or greater); and a U-shape surface morphology with smooth crater, which prevents the formation of cracks in the silicon layers after stacking.

The ZnO:Al layers were sputtered from an Al₂O₃ (0.5 wt %)-doped ZnO ceramic target and then chemically wet-etched with an HCl-based acid for surface texture formation. It is well-known that the sputtering pressure has a major influence on the structures of sputtered ZnO:Al layers [4] and that the subsequent texturing behavior of a ZnO:Al layer exhibits various features depending on the sputtering pressure [5]. It has been reported that low pressure sputtering conditions, below 1 mTorr, result in a significant increase in carrier mobility and a decrease in etching rate due to the formation of a dense ZnO:Al film.

To fabricate optimal ZnO:Al substrates, we varied the sputtering pressure in the range of 0.5–1.5 mTorr. Unfortunately, deposition under very low pressure often caused micro-arcing in our RF sputtering system, leading to a deterioration in the transparency of the ZnO:Al films. To produce a high-performance TCO with both high transparency and a dense structure, the sputtering pressure and time were both optimized, and, consequently, a two-step deposition process was developed successfully. For the first step, a ZnO:Al layer of 800 nm thickness was prepared at a sputtering pressure of 1 mTorr to achieve a high transparency; then, for the second step, a 0.5 mTorr sputtering pressure was applied to prepare a dense ZnO:Al film on top of this deposited film. The ZnO:Al layer prepared in the second deposition step was approximately 500 nm in thickness.

The ZnO:Al films deposited by this two-step process exhibited a smooth surface (RMS roughness 2–3 nm, determined by AFM measurement) and excellent electrical properties (carrier density (N) = $2.51 \times 10^{20} \text{ cm}^{-3}$ and carrier mobility (μ) = $53 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$). Each deposited ZnO:Al layer was then chemically etched in a mixture of diluted HCl and oxalic acid (C₂H₂O₄) to produce a textured surface morphology. As only the second ZnO:Al layer deposited was etched during this process, the thickness of the resulting textured ZnO:Al layer was approximately 800–900 nm.

Two factors that can increase the current density of a thin-film Si solar cell are high transparency and formation of an optimal light-diffusing structure in the front TCO layer. Fig. 1 compares the optical properties of commercial SnO₂:F substrates (Asahi VU) and the fabricated ZnO:Al substrates. An index-matching liquid, CH₂I₂, and a cover glass were both used to ensure that the diffuse transmittance induced by the textured TCO during the transmittance measurements could be neglected. It is clear that the transmittance of the fabricated ZnO:Al substrate is higher than that of the commercial SnO₂:F substrate at wavelengths above 700 nm. Additionally, while the haze ratio of SnO₂:F is only 2% at a wavelength of 850 nm, the fabricated ZnO:Al exhibits a significantly higher haze ratio of 48%. These enhanced optical properties for the fabricated ZnO:Al layer show potential for improving the short-circuit current of the triple-junction thin-film solar cells produced in this work, especially in the case of bottom cells that include $\mu\text{-Si:H}$, which exhibits a very low absorption coefficient.

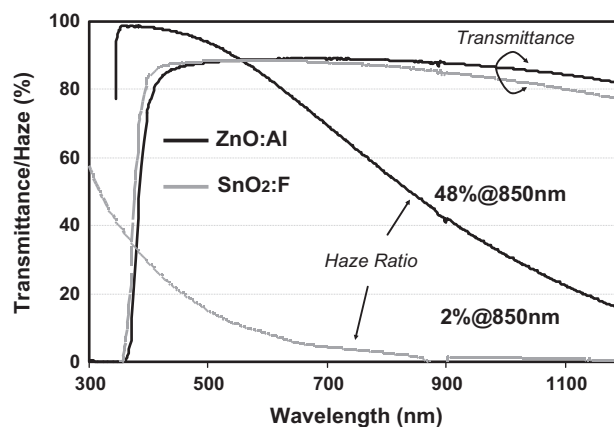


Fig. 1. Optical transmittance spectra and haze ratios of commercial SnO₂:F and fabricated ZnO:Al substrates.

It has been reported that the crystal growth of $\mu\text{-Si:H}$ on steep textures gives rise to crack formation due to collisions in columnar growth, resulting in a reduction of the open-circuit voltage (V_{oc}) and the fill factor (F.F.) [6]. The crack density can be reduced by transforming the V-shape valleys located between pyramids on the TCO surface into U-shaped valleys [7]. Therefore, the surface characteristics of TCO substrates, in addition to their optical properties, should be considered carefully. AFM topographies of the SnO₂:F and ZnO:Al substrates are shown in Fig. 2. Because the surface of the etched ZnO:Al layers exhibited U-shaped valleys with smooth craters, as shown in Fig. 2(b), the crack density in the thin-film solar cells using the ZnO:Al substrate was reduced compared to those using the SnO₂:F substrate. The TEM images for extinct cracks by U-shape valleys are not shown here, but it had similar tendency with previous other report [7]. Hereafter, all single and triple-junction solar cells in this study were prepared on the two-step deposited ZnO:Al substrates.

2.2. A high-performance a-Si:H top cell with a wide bandgap intrinsic layer

Recently, Prof. Konagai's group [2] has calculated the theoretical conversion efficiencies for triple-junction thin-film Si solar cells. These theoretical efficiencies were obtained by varying the bandgaps of the top and middle cells while fixing that of the bottom cell at 1.1 eV, corresponding to the bandgap of the bottom cell in a $\mu\text{-Si:H}$ system. According to the results of this group, the highest conversion efficiency of 21.4% was obtained when the bandgaps of the top and middle cells were 2 and 1.45 eV, respectively. Therefore, for high-efficiency triple-junction solar cells, it is very important to develop high bandgaps and high quality materials for use in the intrinsic layer of the top cell. In our work, the top cell in the triple-junction structure, the purpose of which is to absorb blue light, utilizes an a-Si:H layer with an optical bandgap of approximately 1.7 eV for its intrinsic layer.

The a-Si:H films were deposited on glass substrate via a plasma-enhanced chemical vapor deposition (PECVD) method with a radio frequency (RF) of 13.56 MHz at a substrate temperature of 180 °C. The optical parameters, such as the optical bandgap and film thickness, were determined from ellipsometry measurements by fitting the data to a Tauc–Lorentz dispersion model. Fig. 3 (a) shows the variation in the optical bandgaps of several a-Si:H layers as a function of the H₂/SiH₄ gas flow ratio and the RF power during the PECVD process. The data show that using a higher RF power slightly increases the bandgap of the a-Si:H layer, but it is clear that the H₂/SiH₄ ratio determines the bandgap level more strongly. The bandgap of a-Si:H increased with an increasing H₂

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