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# Performance enhancement of thin-film silicon solar cells by development of core component layers

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## ABSTRACT

High efficiency thin-film silicon (Si) solar cells were prepared on flexible substrates by the plasma-enhanced chemical vapor deposition method. To improve their performance, the microstructural, electrical, and optical properties of the core component layers including the metal rear reflectors, p- and n-type doped layers, and intrinsic absorber layers were controlled sophistically. To enable the use of flexible substrates with low heat resistance as well as to enhance light-scattering properties, nanotextured rear reflectors with a Ag/Al:Si bilayer structure were developed by dc magnetron sputtering at a low substrate temperature of below 150 °C. Highly crystalline n-doped seed layers (which effectively eliminate a defect-dense amorphous region formed in the initial growth stage of intrinsic nanocrystalline silicon (nc-Si:H) absorber layers) and p-type wide-bandgap nanocrystalline silicon carbide (nc-SiC:H) window layers (which reduce the parasitic absorption loss in the short-wavelength region and increase the open circuit voltage ($V_{OC}$)) were successfully applied to enhance the performance characteristics of the solar cells. Through the combination of the developed core component layers, high conversion efficiencies of 8.84% ($V_{OC}$ = 0.53 V, $J_{SC}$ = 25.28 mA/cm$^2$, and fill factor (FF) = 0.66, where $J_{SC}$ is the short circuit current) and 7.48% ($V_{OC}$ = 0.50 V, $J_{SC}$ = 21.07 mA/cm$^2$, and FF = 0.71) were obtained for nc-Si:H solar cells fabricated on stainless steel (SUS) and polyimide substrates, respectively, at a low substrate temperature of below 150 °C. Flexible a-Si:H/nc-Si:H double-junction solar cells fabricated on SUS substrates showed a high conversion efficiency of 11.46% ($V_{OC}$ = 1.38 V, $J_{SC}$ = 11.53 mA/cm$^2$, and FF = 0.72) when the nc-Si:H solar cells developed in this study were applied as a bottom cell.

## 1. Introduction

Low-cost and highly efficient solar cells have been intensively developed to ensure economic feasibility of photovoltaic power generation. Among such solar cells, thin-film Si solar cells are receiving much attention as next-generation solar cells because of their several advantages, such as the use of affordable and abundant Si materials and high volume production capacity (You et al., 2015; Lee and Ebong, 2017). In particular, flexible thin-film Si solar cells, which use lightweight and flexible substrates, have the advantages of easy of installation and transportability and robustness. Thus, their utilization as building-integrated photovoltaics and portable or military power supplies can be anticipated (Neubert et al., 2014; Heinstein et al., 2013). Another advantage of using thin-fill solar cells with flexible substrates is that their manufacturing cost is lower than that of thin-film solar cells with glass substrates, because of the higher throughput of the former achieved through roll-to-roll processing (Zi et al., 2016; Fernández et al., 2015). However, despite all these advantages offered by thin-film Si solar cells, an important technical issue remains to be addressed: their efficiency needs to be improved, since it is relatively lower than that of crystalline Si solar cells or other compound thin-film solar cells. There are several challenges to achieve this improvement: light management, defect control in the absorber layer and at its interfaces, and development of new materials to be used in the absorber and doped layers.

In the present study, possible approaches for achieving a high conversion efficiency of flexible hydrogenated nanocrystalline silicon (nc-Si:H) thin-film solar cells with an n-i-p configuration fabricated by plasma-enhanced chemical vapor deposition (PECVD) were proposed. Recently developed element technologies, such as surface-textured rear reflectors, n-type doped seed layers for controlling the initial microstructure of intrinsic nc-Si:H absorbers, and wide-bandgap p-type

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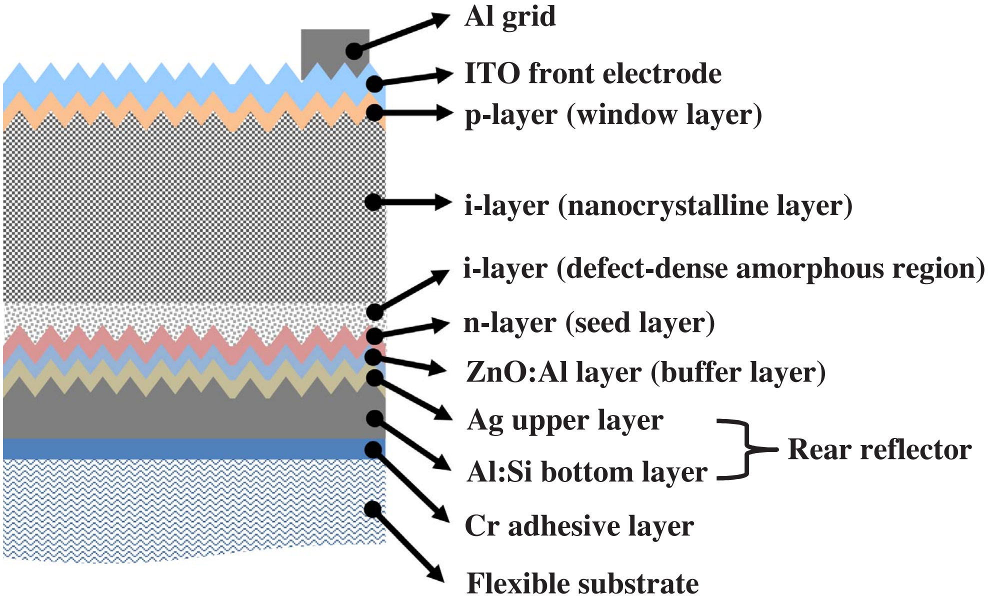

**Fig. 1.** Schematic diagram of nc-Si:H solar cell fabricated in this study.

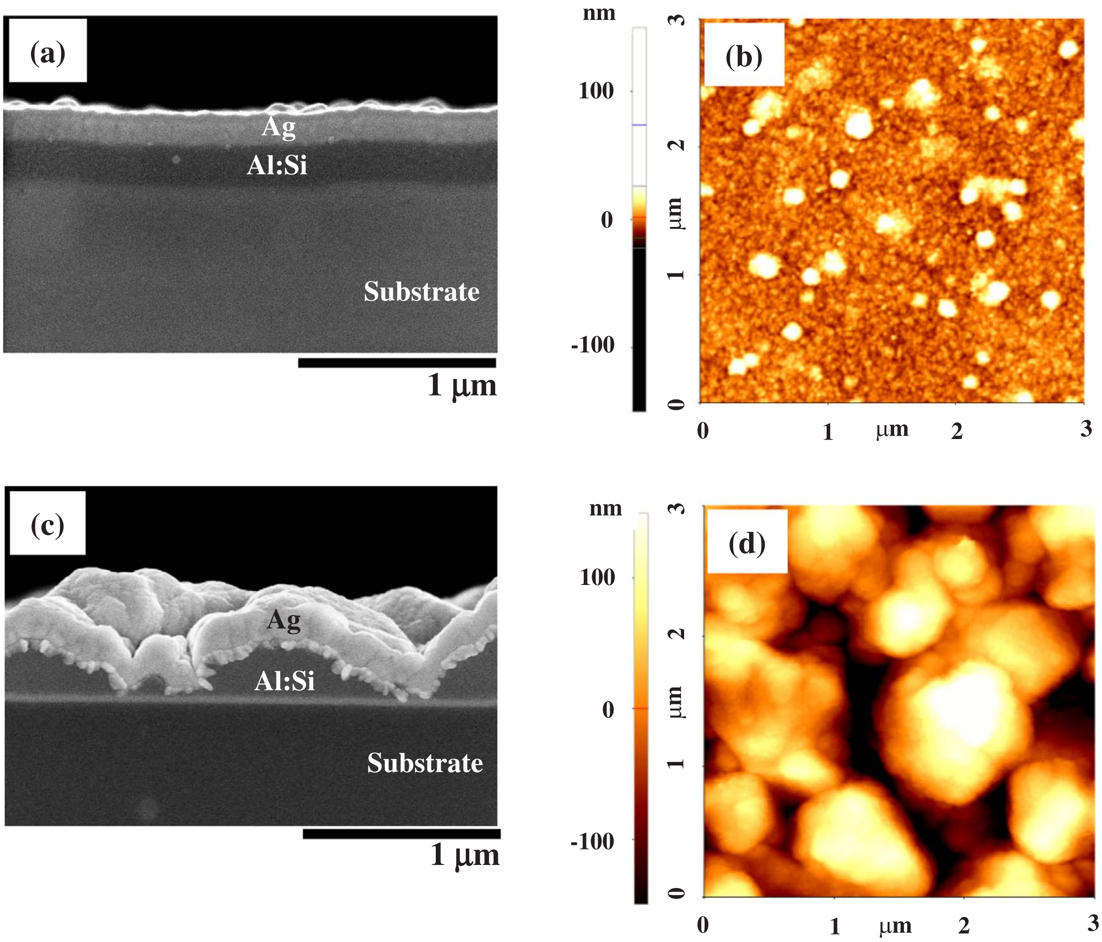

**Fig. 2.** Cross-sectional SEM and AFM images of flat (a, b) and textured (c, d) Ag/Al:Si rear reflectors prepared at low and high $T_S$.

window layers, were introduced. Further, new concepts and structures of these core component layers constituting the solar cells were described systematically, and their effects on the performance of thin-film Si solar cells were investigated.

## 2. Experimental section

Fig. 1 shows a schematic diagram of a flexible nc-Si:H thin-film solar cell with an n-i-p stacked structure prepared in this study. The device structure was as follow: flexible substrate/Cr adhesive layer (20 nm)/ metal rear reflector/ZnO:Al buffer layer (100 nm)/n-nc-Si:H(45 nm)/i-