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The low-temperature deposition of textured multilayer back reflectors with enhanced light-scattering properties on polymeric substrates

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ABSTRACT

In this article, we report on the low-temperature deposition of textured back reflectors using sputtered ZnO:Al/Ag/Al:Si layers in flexible nanocrystalline silicon (nc-Si:H) thin-film solar cells. The surface morphology of this multilayer system depends on that of the Al:Si bottom layers, whereas its optical properties are determined by the Ag and ZnO:Al films deposited on top of the Al:Si layers. The nc-Si:H thin-film solar cells fabricated on textured ZnO:Al/Ag/Al:Si multilayer back reflectors showed an enhanced spectral response for wavelengths between 650 nm and 1100 nm when compared with cells with flat multilayer back reflectors. A high conversion efficiency of 7.25% was successfully achieved for a solar cell with a moderately textured ZnO:Al/Ag/Al:Si multilayer back reflector with a root-mean-square roughness (σ_{rms}) of 30.2 nm deposited at low substrate temperature of 75 °C in which an additional current gain of 2 mA/cm^2 was obtained by effective light scattering from the textured surface without any reduction in the open circuit voltage and the fill factor compared with a solar cell with the flat multilayer back reflector with σ_{rms}=9.13 nm. This result confirms that textured ZnO:Al/Ag/Al:Si multilayer back reflectors prepared at a low substrate temperature of 75 °C can be used in flexible silicon thin-film solar cells using polymeric substrates with low heat resistance.

1. Introduction

Flexible silicon thin-film solar cells using thin metal and polymer substrates have been considered a next-generation photovoltaic device because they can be manufactured at low cost using a roll-to-roll process and enable the creation of customized and innovative designs with a variety of applications [1–3]. The use of abundant and inexpensive nontoxic materials allows high-volume production and promotes the dissemination of solar modules [4,5]. For thin-film solar cells using hydrogenated amorphous (a-Si:H) and nanocrystalline (nc-Si:H) silicon absorbers, a light-trapping strategy is crucial for improving the absorption of incident light because silicon-based materials absorb relatively little light. The optical path length of the incident light can be increased by a factor of $4n^2$ by using materials with ideally textured front and back interfaces. This light trapping leads to a drastic increase in the amount of light absorbed by the solar devices, resulting in an increase in the photo-induced current [6]. In the flexible silicon thin-film solar cells fabricated in the n–i–p deposition sequence, the rough interfaces of the silicon thin-film absorbers are next to surface-textured metal back reflectors [7]. Therefore, a cell's performance is largely dependent on the surface features of its metal back reflector. A direct relationship has been established between the total and diffuse reflectance and the current gain in a solar cell [8].

In this study, we have developed a low-temperature deposition process for textured ZnO:Al/Ag/Al:Si multilayer back reflectors used in flexible nc-Si:H solar cells that uses polyimide substrates and a magnetron sputtering process. This low-temperature process is expected to have advantages in the roll-to-roll process for creating flexible thin-film photovoltaic devices because the high-temperature process used with the moving substrates is very difficult and complex and is not suitable for cost-effective mass production. How the variations in the microstructural and optical properties of the ZnO:Al/Ag/Al:Si layers depend on the substrate temperature was systematically investigated, and their influence on the performance of flexible nc-Si:H solar cells was evaluated.

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2. Details of the experiments

2.1. The deposition of multilayer back reflectors

The 50-μm-thick polyimide (PI) substrates were cut into $5\times5\ cm^2$ pieces and were cleaned ultrasonically in acetone, isopropyl alcohol and distilled water to remove any surface contamination. The dc-sputtered 20-nm-thick Cr films were deposited on the clean PI substrates to improve the adhesion between the substrate and the multilayer film. The film deposition was carried out by dc-magnetron sputtering for the Al:Si and Ag metal films and by rf-magnetron sputtering for the ZnO:Al film. The 4-in.-diameter high-purity Al:Si (1 wt% Si) and Ag metal targets and the ZnO:Al (2 wt% Al_2O_3) ceramic target were used as source materials. The sputtering chamber was evacuated to a base pressure below 7×10^{-5} Pa using a turbo molecular pump and a rotary pump. Pure Ar gas (99.999%) with a flow rate of 10 sccm (ml/min) was introduced as a sputter gas and the chamber pressure was maintained at $1\text{–}2\times10^{-1}$ Pa during the deposition process. The target-to-substrate distance was fixed at 100 mm. The plasma power density was held constant at 1.23 W/cm^2 for the Al:Si and Ag films and at 1.85 W/cm^2 for the ZnO:Al film. The thickness of each film was varied by controlling the sputtering time. The Al:Si films were deposited by varying the substrate temperature (T_s) from 25 °C to 100 °C to induce evolution of the surface morphology; then, the Ag film was deposited to enhance the optical reflectivity. Finally, the ZnO:Al films acting as barriers to the metal films were deposited on the Ag/Al:Si bilayers. The Ag and ZnO:Al films were prepared without intentional heating to minimize the effect of heat on the surface texture of the Al:Si films. Details of the experimental set-up and the deposition conditions are listed in Table 1.

2.2. The fabrication of flexible nc-Si:H solar cells

N–i–p substrate-type nc-Si:H thin-film solar cells were fabricated on ZnO:Al/Ag/Al:Si multilayer back reflectors using plasma-enhanced chemical vapor deposition (PECVD). The intrinsic and doped layers were deposited using a 60 MHz very high frequency (VHF) and a 13.56 MHz radio frequency (RF) glow discharge, respectively. The 1-μm-thick intrinsic nc-Si:H layers were deposited using a mixture of SiH_4/H_2 (7:120 sccm) at a plasma power density of 0.1 W/cm^2, a pressure of 40 Pa and a substrate temperature of 150 °C. For p- and n-doping, B_2H_6 (1% in H_2) and PH_3 (1% in H_2) gases were added to SiH_4, H_2 and CH_4 (50% in H_2), respectively. The 80-nm-thick indium tin oxide (ITO) layers were prepared by rf-magnetron sputtering using an ITO target (5 wt% SnO_2) in an Ar atmosphere. The individual solar cells, which had areas of $0.5\times0.5\ cm^2$, were defined using a shadow mask during the ITO film deposition. The Al metal grids were deposited using thermal evaporation. The complete device sequence was as follows: PI substrate/Cr (20 nm)/multilayer back reflector (ZnO:Al (100 nm), Ag (180 nm), Al:Si (300 nm))/n-nc-Si:H (30 nm)/i-nc-Si:H (1 μm)/p-nc-SiC:H (20 nm)/ITO (80 nm)/Al grid. Fig. 1(a) and (b) shows a schematic diagram and a photograph, respectively, of a flexible nc-Si:H solar cell prepared using a multilayer back reflector on PI substrate.

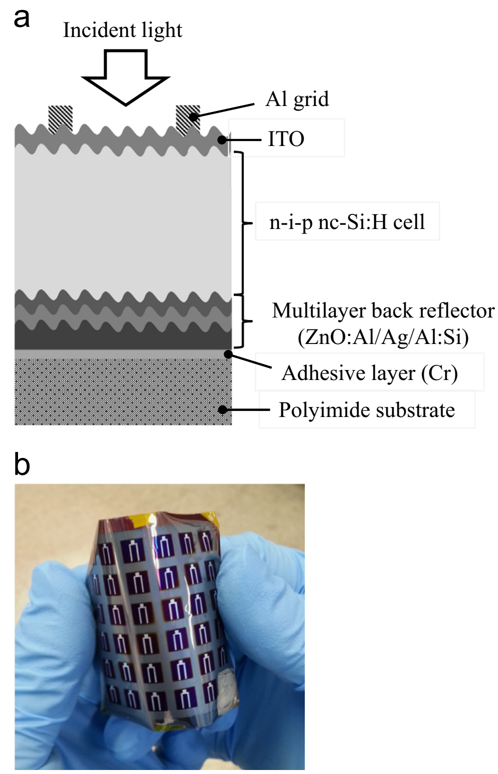

Fig. 1. A schematic diagram (a) and photograph (b) of the flexible solar cell prepared on ZnO:Al/Ag/Al:Si multilayer back reflectors using a polyimide substrate.

2.3. Characterization techniques

The microstructure and the surface morphology of the deposited films were investigated using a Hitachi S-4800 scanning electron microscope and a Park System XE-100 atomic force microscope, respectively. The optical properties of the samples were measured using a spectrometer (Shimazu UV-3101PC) with an integral sphere. The conversion efficiency (η) of the solar cells

Table 1
The experimental set-up and deposition parameters of the ZnO:Al/Ag/Al:Si multilayer back reflectors.

Parameter		Value		
Target		4 in.-Al:Si (Al 99 wt%:Si 1 wt%)		
		4 in.-Ag		
		4 in.-ZnO:Al (ZnO 98 wt%:Al_2O_3 2 wt%)		
Target–substrate distance (mm)		100		
Base pressure (Pa)		$<7\times10^{-5}$		
Working pressure (Pa)		$1\text{–}2\times10^{-1}$		
Sputtering gas and flow rate (sccm)		Ar, 10		
Plasma and power density (W/cm^2)		DC, 1.23 for Al:Si and Ag		
		RF, 1.85 for ZnO:Al		
Deposition temperature for Al:Si films	Heater temperature (°C)	25	150	200
	Substrate temperature (°C)	25	75	100
Film thickness (nm)	Al:Si	300		
	Ag	180		
	ZnO:Al	100		