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Integration of subwavelength optical nanostructures for improved antireflection performance of mechanically flexible GaAs solar cells fabricated by epitaxial lift-off

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ABSTRACT

We demonstrate the integration of subwavelength moth-eye and Al_2O_3 nanoisland structures fabricated on polymer packaging sheets and the surface of conventional Al_2O_3/TiO_2 bilayer antireflection coatings, respectively, with epitaxial lift-off single-junction GaAs solar cells. The mechanically flexible cell structure with the integrated optical nanostructures shows substantially improved photovoltaic performance under various incident angles and bending radii compared to devices without such structures: the increase in short-circuit current density arising from integration of these nanostructures ranges from 9% at normal incidence to 52% at 80° incidence; and the reduction in short-circuit current density under moderate bending decreases from 9.7% to 6.7%.

1. Introduction

The epitaxial lift-off (ELO) process [1–3], which enables the separation of epitaxially grown thin-film device layers from their original growth substrates and reuse of growth substrates, can be employed to produce mechanically flexible, low-cost, light-weight, and high-efficiency GaAs thin-film solar cells. Since thin-film flexible ELO solar cells [4,5] are likely to be deployed with illumination incident over a larger range of orientations, e.g. for applications such as mobile solar systems [6,7], the need to reduce optical reflection loss of flexible ELO cells over a broad range of incident angles is greater compared to that of rigid cells. Conventional stacked planar thin-film antireflection coatings are only able to provide excellent antireflection performance at normal incidence and for small incident angles [8]. In order to achieve better broad-spectrum, omnidirectional antireflection performance, various approaches using subwavelength nanostructures have been reported. These can generally be grouped into two categories: nanostructures fabricated on substrates with high [9–11] and low [12–15] refractive indices. In prior work, the efficacy of such approaches has been demonstrated in fully packaged, rigid GaAs solar cells [19]. However, a complete demonstration of integrated nanostructures on commercial-grade, flexible ELO cells and with polymer packaging material for broadband, omnidirectional antireflection in photovoltaic applications has not been reported.

In this work, we demonstrate the integration of a moth-eye textured polyethylene terephthalate (PET) packaging sheet combined with Al_2O_3 nanoisland structures on 1 cm × 1 cm flexible ELO single-junction GaAs solar cells. A high-throughput, low-cost nanosphere lithography (NSL) process [16–20] is used to create moth-eye nanostructures and Al_2O_3 nanoislands on the PET packaging sheet surface and ELO GaAs cell surface, respectively. Measurements show that the ELO GaAs cell integrated with moth-eye textured PET packaging sheet and Al_2O_3 nanoislands exhibits greatly improved short-circuit current density (J_{sc}) compared to the cell with conventional Al_2O_3/TiO_2 bilayer antireflection coating and unpatterned PET packaging sheet over a wide range of incident angles: a 9% increase in J_{sc} is observed at normal incidence, and a 52% increase in J_{sc} is observed at 80° angle of incidence. Current–voltage measurements reveal that the ELO cell integrated with a moth-eye textured PET packaging sheet and Al_2O_3 nanoislands shows a much less reduced J_{sc} compared to the cell without optical nanostructures under a moderate bending condition: 9.7% reduction in J_{sc} for the cell integrated with optical nanostructures in contrast with 6.7% reduction in J_{sc} for the cell

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without optical nanostructures is observed. The self-cleaning properties of the moth-eye textured PET packaging sheet are evaluated by measuring the contact angle of water droplets on the sheet surface, which shows that the moth-eye textured PET packaging sheet has substantially improved self-cleaning property compared to the unpatterned PET packaging sheet.

2. Experiment

GaAs single junction solar cells were grown on GaAs (001) substrates by metallorganic chemical vapor deposition (MOCVD) at 100 Torr using Arsine (AsH_3), Phosphine (PH_3), Trimethylindium (TMI) and Trimethylgallium (TMG) as precursors with a V/III ratio > 50. The growth structure consisted of InGaP window and back surface field (BSF) layers, a 3.5 μm GaAs base layer with $2 \times 10^{17}\ \text{cm}^{-3}$ p-type doping, a 0.1 μm GaAs emitter with n-type doping in the range of $2 \times 10^{18}\ \text{cm}^{-3}$, and a 5 nm AlAs release layer. The epitaxial lift-off process was performed via a procedure similar to that reported elsewhere [7]. Current–voltage characteristics were measured with HP4156A precision semiconductor parameter analyzer, using unpolarized normally incident light from a Newport Oriel 96000 solar simulator operating under irradiation intensity of 100 mW/cm^2 with an airmass (AM) 1.5G filter, and at a temperature of 25 °C. The irradiation intensity from the solar simulator was calibrated using a commercial-grade calibrated single-junction GaAs solar cell (Spire Corp. Lot# 567-5-2). Photocurrent response spectra were measured at zero bias under unpolarized light from a single grating monochromator based system from Optronic Laboratories (OL750) with AC lock in detection with a chopping frequency of 188 Hz. A calibration of the illumination intensity of the monochromator was performed using the calibrated single-junction GaAs solar cell (Spire Corp. Lot# 567-5-2) with a reported spectral response. The PET packaging sheet is attached to the cell substrate using a space-grade encapsulant (Dow Corning 93-500, with a refractive index ~1.41 in the visible wavelength range). A home-made stretcher is used to bend the packaged flexible ELO GaAs cells.

Fig. 1a shows a schematic diagram of an ELO single-junction GaAs cell with conventional Al_2O_3/TiO_2 bilayer antireflection coating integrated with Al_2O_3 nanoisland structure and combined with double-side textured PET packaging sheet, together with the refractive index profile. Fig. 1b–d shows key steps in fabricating the moth-eye textured PET packaging sheet: $D_1 = 200$ nm diameter polystyrene (PS) spheres were deposited on the PET packaging sheet surface using the NSL process (Fig. 1b), followed by reactive-ion etching with 100 sccm of oxygen at a pressure of 200 mTorr and radio frequency power of 100 W for 4 min (Fig. 1c), resulting

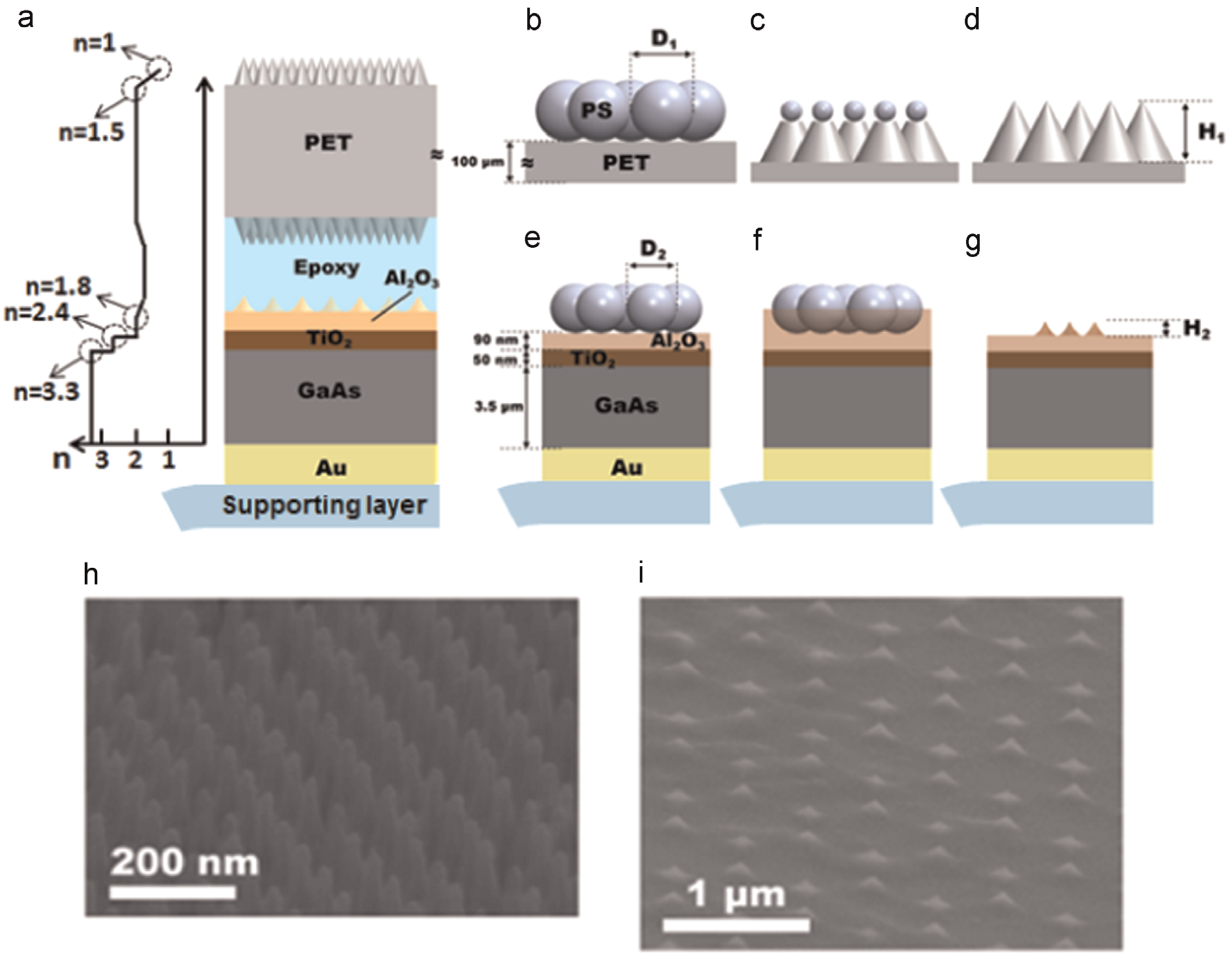

Fig. 1. (a) Schematic diagram of a polymer-packaged GaAs solar cell coated with conventional Al_2O_3/TiO_2 bilayer antireflection coating with Al_2O_3 nanoislands and integrated with double-side moth-eye textured PET packaging sheet by space-grade encapsulant, together with the vertical refractive index profile. (b)–(d) Schematic diagrams of process flow for fabricating moth-eye structure on PET substrate using nanosphere lithography with polystyrene spheres (PS). (e)–(g) Schematic diagram of process flow for fabricating Al_2O_3 nanoislands structure on Al_2O_3/TiO_2 bilayer antireflection coating. (h) SEM image of the completed moth-eye structure on PET substrate. (i) SEM image of the completed nanoislands structure.