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Flexible space solar cell array with radiation shield fabricated by guided-printing of cover glasses

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ABSTRACT

As the main electrical power source of spacecraft, solar cells require high electrical performance and light weight, to provide enough electrical power for missions in space and to lower costs for launching. Multi-junction compound semiconductor solar cells generate relatively high power, but their rigid substrates are tens or hundreds of times thicker than the solar cells. In this paper, methods are described to realize flexible space solar cell arrays that can be wrapped on non-planar surfaces, by removing the rigid substrates and integrating the thin solar cells on flexible substrates. Cover glasses were integrated over the solar cells on flexible substrates through an guided-printing method, providing both flexibility and radiation shielding. Experimental results and mechanical analysis demonstrate the mechanical and electrical performances of these flexible space solar cell arrays.

1. Introduction

In space, satellites, space stations, and rovers use solar cells as their main power source. In such applications, III-V multi-junction compound semiconductor solar cells have been one of the most frequently used solar cells because of their high electrical performance and radiation hardness [1–5]. Recently, processes to separate the thin compound semiconductor solar cells from their substrates without degrading electrical performance, called epitaxial lift-off (ELO) or transfer-printing [6–14], have been actively studied in efforts to lower production costs, permit recycling of the original substrates [15–18], and to provide enhanced mechanical flexibility or stretchability [19–21]. Such technologies are particularly beneficial for space applications [22–29]. Separating thin semiconductor solar cells from their rigid substrates can not only provide weight savings that can lower the cost of launches, but also provide mechanical flexibility, so that the solar cells can be stowed in a compact form while launching, or attached onto non-planar surfaces to maximize the areal coverage of the solar cells.

In space environments, however, flexible solar cells need to be shielded from particle radiation and UV radiation to avoid degradation in electrical performances. This is typically accomplished by using optically transparent cover glasses, which are usually rigid and planar. Although flexible cover glasses are being developed [30,31], improvements in reliability are still required. In this paper, we present designs and technologies for fabricating flexible space solar cell arrays that exploit the use of small rigid cover glasses, which are integrated onto the flexible solar cells by guided-printing. The resulting solar cell arrays are both flexible and have an effective radiation shield. We describe the results of experimental measurements and analysis of radiation effects and mechanical flexibility, and then demonstrate the feasibility of the approach using dual-junction GaInP/GaAs solar cells.

2. Materials and method

2.1. Fabrication process of the solar cell array

Firstly, mesa wet etching defined the dual-junction GaInP/GaAs layers on a GaAs wafer. Metallization with an electron beam evaporator formed the contact metals (Ti/Au, 20 nm/60 nm) on the top and bottom contact layers. After removing a sacrificial layer, the separated solar cells from a GaAs wafer were transferred onto a PI (polyimide) film. Sputtering and lift-off processes formed the metal interconnects (Cr/Au, 100 nm/200 nm) for the solar cells.

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2.2. Guided-printing process of the cover glasses

The guides (SU-8, 148 μm ×760 μm ×16 μm) for guided-printing of the cover glasses were formed by photolithography around the solar cells. Cover glasses (CMG 100, QIOPTIQ, thickness: 100 μm, size: 900 μm×900 μm) were diced on a UV releasable tape using a diamond saw and were brought into contact with a PDMS (Polydimethylsiloxane, Sylgard 184, Dow Corning) stamp. UV exposure reduced the adhesion of the UV tape and enabled the PDMS stamp to pick up the diced cover glass array from the UV tape. The cover glasses then were aligned and brought into contact with the solar cells, which were spin-coated with a space-qualified adhesive (93–500, Dow Corning, ~40 μm). The guided-printing process was conducted on a 3D microstage that includes vacuum chucks and an optical microscope. The guides around the solar cells help to align the cover glass array with the flexible solar cell array during the printing of the cover glasses, and subsequent curing of the space-qualified adhesive. Without the guides, misalignment during the curing process occurs. Curing the adhesive for a week at room temperature and retrieving the PDMS stamp finishes the guided-printing process of the cover glasses.

2.3. Irradiation tests

The solar cell arrays were irradiated with protons (1 MeV) generated and accelerated by a particle accelerator (Pelletron). Both solar cell arrays with, and without, cover glasses were put together side by side in the chamber and irradiated at the same time for fair comparison of the irradiation effects, at fluences of 10^{12}, 10^{13} and 10^{14} p/cm^2. The electrical performances of the arrays were measured immediately after each irradiation.

2.4. Measurements of electrical and mechanical characteristics

The current-voltage (I-V) characteristics of the flexible space solar cell arrays were measured at room temperature with a DC source meter (B2900A Series, Keysight) under a solar simulator (LCS-100, Oriel) equipped with a AM0 filter. For comparison, the performance of the solar cell arrays was measured before and after the printing of the cover glass array. Mechanical durability was evaluated by measuring current-voltage characteristics during repeated cycles of bending and unbending of the flexible space solar cell arrays on a cylinder with a radius of a 10 mm. Finite element model (FEM, Abaqus CAE) analysis was conducted to calculate the strain of a solar cell array that was bent with a radius of 10 mm.

3. Results and discussion

3.1. Fabrication of the flexible space solar cell array

The fabrication process of the flexible space solar array starts with wet chemical etching of dual-junction GaInP/GaAs layers on a GaAs wafer with hydrochloric acid (HCl, 35%, OCI) and phosphoric acid (H_3PO_4, 85%, OCI) respectively, to define solar cell mesa regions (760 μm ×760 μm) as reported previously [32]. Metal deposition with electron beam evaporator and lift-off processes formed the contact metals (Ti/Au, 20 nm/60 nm) on the top and bottom contact layers. No front contact grid other than the top contact was formed because the solar cells were very small. After removing a sacrificial layer, the processed solar cells (thickness: ~5.3 μm, size: 760 μm ×760 μm, period: 1148 μm, Layer 2, Fig. 1a) were picked by a PDMS stamp and transfer printed onto PI film (thickness: 12.5 μm, Layer 1) that was spin-coated with an adhesive layer (SU-8, Microchem, 2 μm) [33]. The solar cells printed on the PI film were encapsulated by a transparent SU-8 layer (thickness: 4 μm, Layer 3). Photolithography formed holes (700 μm ×30 μm) in the encapsulation layer for the contact metals. Sputtering and lift-off processes formed the bilayer metal interconnects (Cr/Au, 100 nm/200 nm, Layer 4) via holes in Layer 3 (Fig. S1). Finally, the guides (thickness: 16 μm, size: 760 μm ×148 μm, Layer 5) were formed between the solar cells by photolithography of the SU-8.

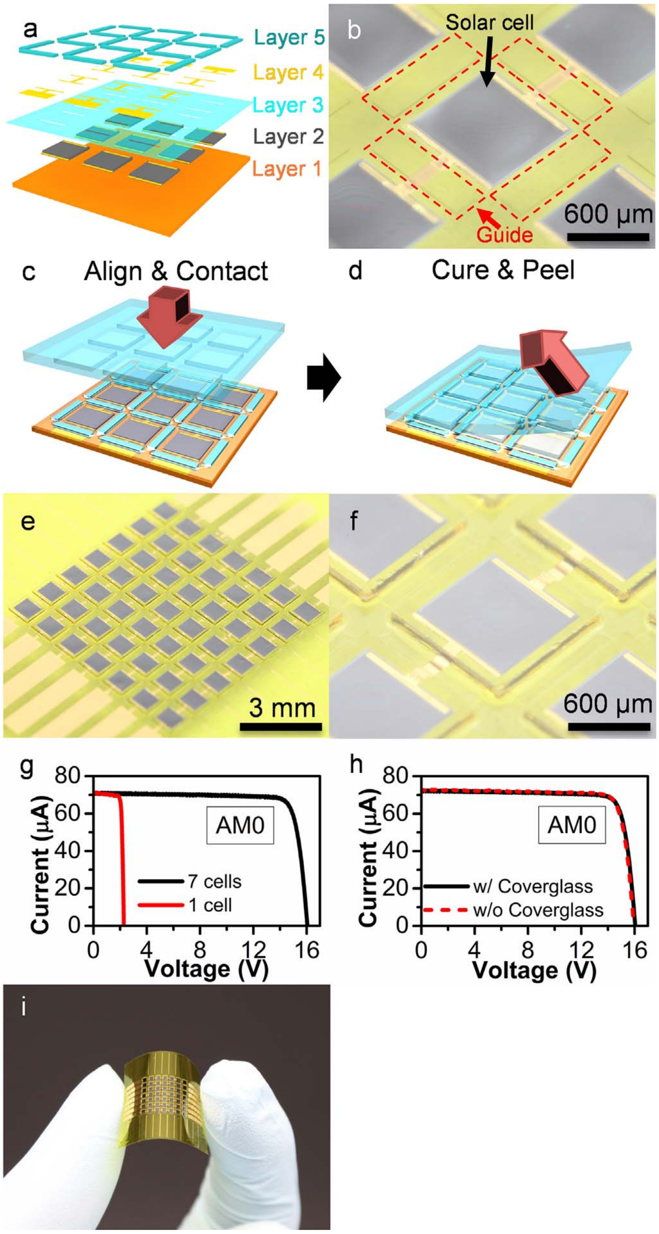

Fig. 1. (a) Exploded view of each layer constituting the solar cell array before printing the space cover glass. [Layer 1: polyimide film (12.5 μm), Layer 2: solar cells (5.3 μm), Layer 3: encapsulation layer (SU-8, 4 μm), Layer 4: metal interconnects (Cr/Au, 100 nm/300 nm) Layer 5: guide (SU-8, 16 μm)] (b) Optical image of the solar cell array prepared for printing of the space cover glass. Dashed rectangles indicate the guides for aligning and printing the cover glass. (c–d) The cover glass guided-printing process. (c) The cover glass array was diced and picked up by a PDMS stamp, then aligned and brought into contact with the solar cells, which were spin-coated with a layer of space-qualified adhesive (~40 μm). (d) Peeling the PDMS stamp after curing the adhesive leaves the cover glass array printed on the solar cells. (e–f) Optical images of the flexible space solar cell (each 760 μm ×760 μm) array covered with the cover glass array (each 900 μm ×900 μm). (g) Current-voltage characteristics of a single solar cell (red) and interconnected solar cells (black, 7 cells in series) under AM 0 illumination. (h) Current-voltage characteristics of the flexible space solar cell array (7 solar cells interconnected in series) under AM0 illumination before (black line) and after printing the cover glass (dashed red line). The current-voltage curves with and without the cover glass are almost identical. (i) Flexible space solar cells array bent by fingers.

The red dashed rectangles (Fig. 1b) around the solar cells indicate the guides used for transfer-printing the space cover glass. The guides'