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High-efficiency Thin and Compact Concentrator Photovoltaics using Micro-solar Cells with Via-holes Sandwiched between Thin Lens-array and Circuit Board

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Abstract

We have developed a compact concentrator photovoltaic (CPV) module that comprises micro-solar cells with a cell size of ~ 0.6 mm × 0.6 mm, sandwiched between a 20 mm-thick lens array and a 1 mm-thick circuit board, with no air gap in the structure. To establish electrical connection between the circuit board and the micro-solar cells, we developed a micro-solar cell structure with via-holes through which the cathode and the anode on the upper face of the cell are electrically connected to electrodes patterned on the lower face of the cell. In this study, we demonstrated that the energy conversion efficiency of the micro-solar cell was close to that of a standard solar cell with dimensions ~ 5 mm × 5 mm, which is commonly used in conventional CPV systems. Our study shows that perimeter carrier recombination effects in micro-solar cells do not impact the performance significantly under concentrated illumination. We assembled our micro-solar cells into a CPV module and demonstrated the module energy conversion efficiency of 33.3% under solar illumination.

1. Introduction

CPV systems are able to realize much higher solar energy conversion efficiency than flat solar panels [1]. In a CPV system, solar cells are placed only at the focal points of concentrator lenses, which significantly reduces the proportion of the cell cost to the total system cost compared to the case of flat solar panels. The state-of-the-art high efficiency tandem solar cells (current record is 44.0% at 942X suns by Solar Junction Corporation [2]) can, therefore, be used in CPV modules without substantially increasing the total cost of the CPV system, and CPV modules can realize high photovoltaic (PV) performance at viable cost.

We have proposed an extremely thin and compact CPV module, one-tenth the thickness of conventional type of CPV modules [3]. Our CPV module is built up by successively stacking, with no air gap, a thin lens array, sub-millimeter-length solar cells, and a circuit board. In such a module, electrical connection between the circuit board and the solar cells is a non-trivial issue. For robust electrical connection, we have developed a unique micro-solar cell structure, in which two via-holes in the upper face of the cell are electrically connected to electrodes patterned on the lower face of the cell. Our micro-solar cell is markedly different in size and cell structure from the "standard" solar cells generally used for conventional CPVs whose size is around 5 mm × 5 mm.

In this study, we develop the unique micro-solar cell structure and investigate the PV characteristics of our micro-solar cell in comparison with those of a standard solar cell. We demonstrate that our micro-solar cell achieves comparable performance to that of a standard solar cell under concentrated illumination.

2. Experiment and results

Figure 1(a) shows a photograph of our CPV module. In this CPV module, the solar cells are directly attached to the lower face of a lens array and electrically connected to a circuit board beneath the cells, as shown in Fig. 1(b). The cell size is ~ 0.6 mm × 0.6 mm (defined by the size of the patterned epitaxial layers as shown in Figure 1 (c)) and two via-holes through which the cathode and anode on the upper face of the cell are electrically connected with the electrodes that are patterned on the lower face of the cells, as shown in Fig. 1(c). The electrodes on the lower face of the cell are electrically connected with the circuit board using solder paste.

The micro-solar cells were fabricated using the following method. A highly doped GaAs lower conduction layer and triple-junction solar cell consisting of GaInNAsSb/GaAs/InGaP layers were epitaxially grown on a semi-insulating GaAs substrate. A cathode grid electrode and anti-reflection coating (ARC) were applied. The epitaxial layer and the contact layer were then patterned by wet etching, and the side walls of the resultant mesa structure were covered with organic polymer film. Subsequently, two via-holes, 70 μm in diameter and about 140 μm deep, were fabricated on the upper face of the wafer by dry etching. The via-holes were then refilled by means of Au electro-plating and then individually electrically connected with the grid electrode and the lower conduction layer. The lower face of the wafer was thinned by mechanical lapping to 100 µm to expose the refilled metal on the back surface, and Au bumps were patterned on the lower face of the substrate. Finally, the wafer was diced to make individual micro-solar cells.

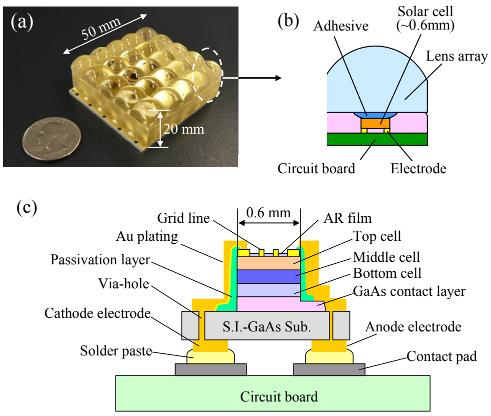

Figure 1. (a) Photograph of the CPV module, (b) schematic sectional image of the CPV module, and (c) micro-solar cell.

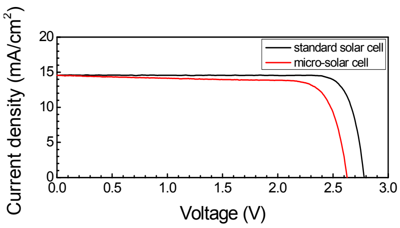

Figure 2. PV characteristics of solar cells under one sun using a solar simulator.

Table I PV characteristics of solar cells under one and ~ 500 suns.

	Micro-solar cell		Standard solar cell	
	1X	468X(flash tester)	1X	533X(flash tester)
η (%)	30.4	40.2	32.6	40.7
V_{OC} (V)	2.63	3.37	2.78	3.44
FF	0.80	0.84	0.86	0.86

We also tested a solar cell with the same triple junction epitaxy with a cell size of ~5 × 5 mm for comparison with the micro-solar cell. The cell structure is the same as those generally used for conventional CPVs: a cathode grid electrode was fabricated on a triple junction epitaxial layer grown on a conductive GaAs wafer and the anode was deposited on the lower face of the wafer. The epitaxial layer and ARC of the solar cell were almost identical to those used for our micro-solar cell. We refer this solar cell as “standard” solar cell.

Figure 2 and Table I show the *I-V* curves and PV characteristics, respectively, of the micro and standard solar cells. Under one sun illumination, open circuit voltage (V_{OC}) and fill factor (FF) of the micro-solar cell were smaller than those of the standard solar cell, which resulted in lower efficiency (η) of the micro-solar cell. We attribute the reduction of V_{OC} in the micro-solar cell to the perimeter recombination current, which manifests itself as enhanced dark current in the micro-solar cell (not shown here) [4]. The reduction of FF in micro-solar cell is mainly due to the lower shunt resistance, presumably caused by leakage through side walls, as observed in the *I-V* curve in Figure 2.

On the other hand, under ~ 500 suns, the differences in V_{OC}, and FF between the micro and standard solar cell were smaller than those under one sun, resulting in the η of the micro-solar cell as high as that of the standard solar cell, as shown in Table I. This indicates that the impact of perimeter becomes insignificant under highly concentrated sunlight. One obvious reason is that the ratio of leakage current (which manifests itself as shunt resistance) to the photocurrent becomes smaller by more than two orders of magnitude under concentration and the impact of leakage becomes negligibly small. Another reason we presume is that, under high concentration, photocurrent is so high that the bulk diffusion current (which is proportional to *exp* ($-qV / k_BT$)) is dominating at V_{OC} as opposed to the recombination current (which is proportional to *exp* ($-qV / 2k_BT$)). Furthermore, as FF of micro-solar cell is comparable to the standard cell, the series resistance of our via-hole structure is sufficiently low for illumination of high-concentrated sunlight. These results indicate that the micro-solar cell we developed can achieve comparable PV characteristics to standard solar cell with much larger active area for CPV applications.

We assembled CPV modules with the micro-solar cells, as shown in Figure 1 (a) and (b), and measured their PV characteristics outdoors in Kyoto, Japan on October 29, 2012 (ambient temperature = 23.4 ˚C, wind speed = 0.9 m/s, direct normal solar irradiation of 788 W/m^2). From the measurements, we demonstrated the peak module efficiency of 33.3 % with V_{OC} 3.25 V and FF 0.80.

3. Conclusions

We have developed a micro-solar cell with a cell size of ~ 0.6 mm × 0.6 mm that employs via-holes to electrically connect the cell on its lower face with a circuit board for building into a CPV module. The PV characteristics of the micro-solar cell were comparable to those of solar cells with larger areas used in conventional CPVs. The CPV module we assembled with micro-solar cells demonstrated an energy conversion efficiency of 33.3 % under solar illumination. This result indicates that the micro-solar cell we have developed can enable our CPV module concept to achieve high PV performance at a low cost.

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