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Multiple-Connected Solar Cells Used by Band-Gap Induced Cascaded Light Absorption

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Abstract. We propose multiple-connected solar cells with different band gaps causing specific light absorption. A commercial three-serial connected a-Si solar cell and a single c-Si solar cell were placed facing each other with an angle of 10 degrees. Those solar cells were electrically connected by electrical wires to form a series circuit. AM1.5 light at 1 sun was slantingly shined to the a-Si solar cell. The top and rear surface of the a-Si solar cell reflected light with photon energy lower than its band gap. The reflected light was illuminated to the c-Si solar cell facing the a-Si solar cell. Solar cell characteristic was obtained with an open circuit voltage V_{oc} of 3.2 V, while the individual a-Si and c-Si cells had V_{oc} of 2.6 and 0.55 V, respectively. The high V_{oc} demonstrates that solar light is effectively used to generate electrical power by cascade-type light absorption by each solar cell component.

Introduction

Crystalline silicon solar cells have been widely developed and applied as a device for generating electrical power directly from sunlight [1,2]. Crystalline silicon has a band gap energy of 1.12eV at room temperature, which locates in the low energy tail region of sun light spectrum on the earth with the AM 1.5 condition, as shown in Fig. 1. Therefore, crystalline silicon effectively absorbs sunlight with photon energy higher than its band gap. However, crystalline silicon solar cells have the limitation of the power conversion efficiency of 28.9 % [3]: it means that 71% of sunlight power doesn't contribute to generation of electrical power. Light with photon energies higher than the band gap is absorbed and hole electron pairs are generated in silicon solar cells. The hole and electron pairs lose their energy to the bad gap energy. And open circuit voltage V_{oc} is limited by the built-in potential in the solar cells. Light with very high photon energy is therefore not efficient for producing electrical power by silicon solar cells. To solve this problem and increase the conversion efficiency, multi-junction solar cells combined with wide- and narrow-band gap semiconductor pn junctions have been developed. Epitaxial crystalline growth method has been widely studied to fabricate wide band gap pn junction layers on narrow band gap pn junction layers [4]. On the other hand, the method of stacking individual solar cells using conductive and transparent gel has been also investigated [5].

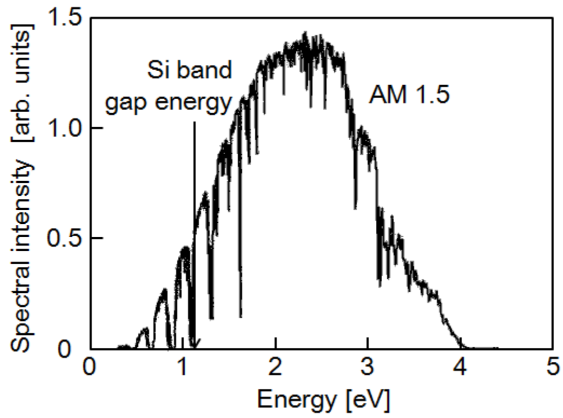
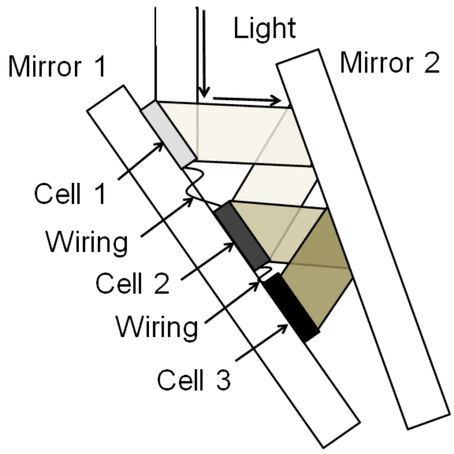


Fig.1 AM 1.5 sunlight spectrum

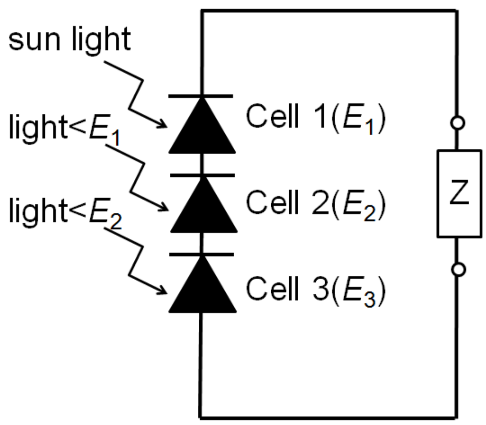
In this paper, we propose a simple method of connection of individual solar cells with different band gaps. We first discuss the principle of the present method, which essentially uses specific absorption characteristics of semiconductor with different band gap energies and designs a geometrical construction of wide and narrow band gap solar cells. Then we report principal demonstration of effective usage of sunlight by multiple-connected solar cell with amorphous-silicon a-Si solar cell with crystalline-silicon c-Si solar cell. Increase in V_{oc} is achieved with the present method.

Principle of multiple-connected solar cells

We discuss connection of three different types of solar cells named cell 1, cell 2 and cell 3. Their band gap energies E_1, E_2, and E_3 are high, middle and low, respectively. Those cells are orderly placed on an inclined mirror substrate (mirror 1), as shown in Fig.2(a); the cells 1, 2, and 3 are placed the highest, middle and the lowest positions, respectively. The cells 1 and 2, and the cells 2 and 3 are connected by electrical wires each other with keeping configuration of pn and pn series equivalent circuit, as shown in Fig. 2(b). Three all connected cells works as solar cell with two output terminals. The cell 1 with E_1 is illuminated with sunlight. The cell generates electrical power by absorbing light with photon energy higher than E_1. On the other hand, because the light with photon energy lower than E_1 is not absorbed, it is reflected outside of the cell 1 by the top and rear surfaces of the cell, metal electrodes formed at the top and rear cell surfaces as well as the underlying mirror 1. The reflection light from the cell 1 is again reflected by another mirror plate (mirror 2) placed facing the three cells with a small angle, as shown in Fig. 2(a). The cell 2 is therefore illuminated with light with photon energy lower than E_1. It generates electrical power by absorbing light with photon energy higher than E_2. In the similar way of the cell 1, the light with photon energy lower than E_2 is reflected outside of the cell 2 by the top and rear surfaces of the cell, metal electrodes formed at the top and rear cell surfaces as well as the underlying mirror 1. The reflected light is illuminated to the cell 3 by the system shown in Fig. 2(a). The cell 3 finally generates electrical power by absorbing light with photon energy higher than E_3. The three solar cells therefore generate electrical power by absorbing light with photon energy specifically determined by their own band gaps. It means that sunlight is more effectively used for generating electrical power compared with a solar cell with single band gap energy. Electrical connection of the three cells expressed by the equivalent circuit shown in Fig. 2(b) gives a high



(a)



(b)

Fig.2 Schematic images of a multiple-connected solar cell (a) and its equivalent circuit. Z is an impedance loaded in the circuit.

V_{oc}, which is the sum of V_{oc} of the three each cell. On the other hand, the short circuit current I_{sc} is limited by the minimum I_{sc} among the three cells. Selection of band gap energies is therefore the most important to achieve high I_{sc} and high electrical power. A solar cell with high band gap energy gives a high V_{oc} in general. High photon flux and high quality cell is necessary for achieving I_{sc} for a solar cell with high band gap energy. This is the same subject of multiple junction solar cells. The selection of solar cells with appropriate band gaps that give the optimum current matching is important under the condition of the black-body radiation spectrum of sun light with the peak intensity at 2.3 eV [6].

Experimental procedure

In order to fundamentally demonstrate the present idea of the multiple-connected solar cell, a commercial three-serial connected a-Si solar cell with a size of 30 mm x 15 mm and a single c-Si solar cell with 35 mm x 25 mm were used. Although the a-Si solar cell has high band gap energy about 1.8 eV, many intrinsic defect states limit I_{sc} and the conversion efficiency low. In this paper, we concentrate observation of high V_{oc} to demonstrate the idea to the multiple-connected solar cell. The optics was constructed using two mirror plates and a fiber-type AM 1.5 solar simulator light, as shown in Fig. 3. The a-Si solar cell was placed on the first mirror using an adhesive tape. The first mirror slantingly set with an angle of 60 degrees to the horizontal metal plate. The c-Si solar cell was also placed on the second mirror facing the a-Si cell. The second mirror had an angle of 70 degrees to the horizontal plate. The two cells were faced each other with the 10 degrees. The light reflected by the top and rear surfaces of a-Si solar cell was successfully irradiated to c-Si solar cell by the arrangement with 10 degrees. Their electrode terminals were connected with an electrical wire. The other electrode terminal of the each cell was connected an electrometer to obtain solar cell characteristics. The a-Si solar cell was slantingly illuminated with AM1.5 light at 1 sun over the whole area. The c-Si solar cell was illuminated with light reflected by the top and rear surfaces of a-Si over the whole area. The filter of 400 nm thick a-Si film with an optical band gap of 1.8 eV formed on a glass substrate was placed between the a-Si and c-Si cells to check power generation of the c-Si solar cell by light with photon energy lower than the a-Si band gap energy. Solar cell characteristic of the each solar cell was also measured when it was placed their own position on their mirror substrate and the partner cell was not placed on the mirror yet. The electrode terminals of the each solar cell were directly connected to the electrometer in the case of measurement of individual solar cells.

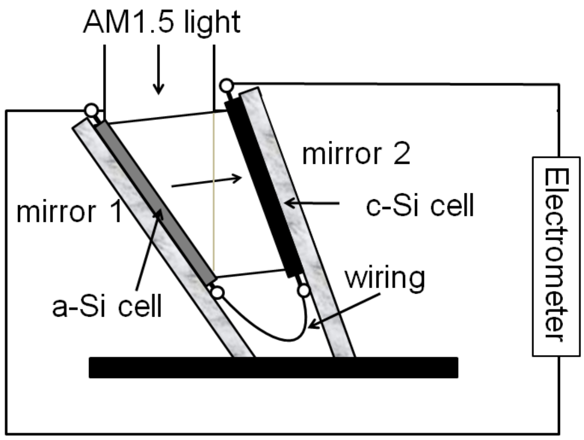


Fig.3 Schematic experimental structure of a-Si and c-Si connected solar cell and a measurement system of its characteristics.

Results and discussion

Figure 4 shows solar cell characteristics for individual samples of the a-Si (a) and the c-Si solar cells (b), respectively. Typical solar cell characteristics were obtained for the two solar cells. The a-Si solar cell gave a high V_{oc} of 2.6 V because of high band gap energy and the three-serial connected type structure. On the other hand, I_{sc} was low of 19 mA because of defective amorphous property. Fill Factor FF of the a-Si solar cell was 0.57. On the other hand, the c-Si solar cell gave a low V_{oc} of 0.55 V because of the low band gap energy. In contrast, I_{sc} was very high of 220 mA because of good crystalline properties with long carrier lifetime. FF was 0.63. In those solar cell conditions reported above, there is no current matching. In the case of connection of a-Si and c-Si solar cells, I_{sc} is therefore limited by that of a-Si solar cell. Figure 5 shows characteristic of the solar cell formed by connection of the a-Si and c-Si solar cells, as shown in Fig. 3. Typical solar cell characteristic was obtained. V_{oc} was 3.2 V, which was the same as the sum of V_{oc} of the two each cell. I_{sc} was 19 mA, which was the same value as that of the a-Si solar cell, as expected. FF was 0.60, which was slightly higher than that of the a-Si solar cell because of the assist for increase in V_{oc} by the c-Si cell.

At the short circuit condition, the a-Si and c-Si solar cells were internally biased each other at the condition of the same current condition. The absolute value of the bias was almost the same of V_{oc} of the c-Si solar cell because the c-Si cell had much higher current than that of the a-Si cell. The a-Si cell was therefore biased at -0.55 V for the short circuit condition. This resulted in shift of solar cell characteristic to the positive voltage direction, as shown in Fig. 5. The voltage of maximum power point V_{mp} increased from 1.8 (single a-Si cell) to 2.3 V in the case of a-Si and c-Si connected cell.

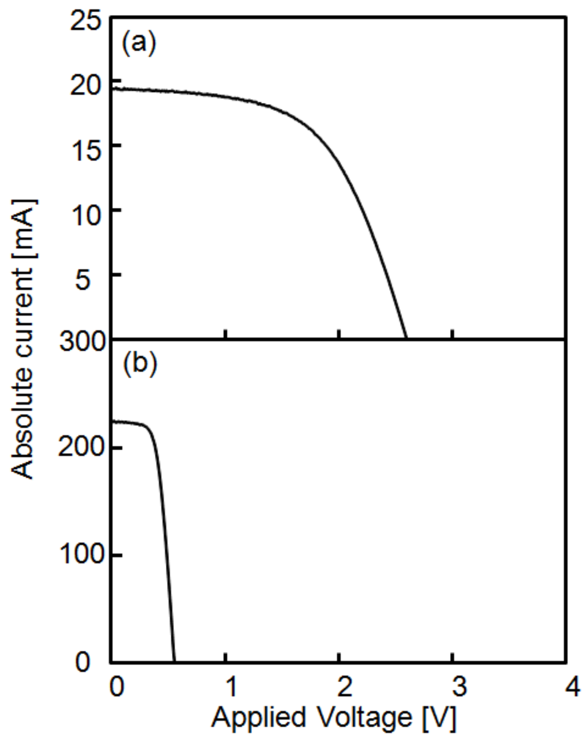


Fig.4 Solar cell characteristics of individual a-Si (a) and c-Si solar cells (b).

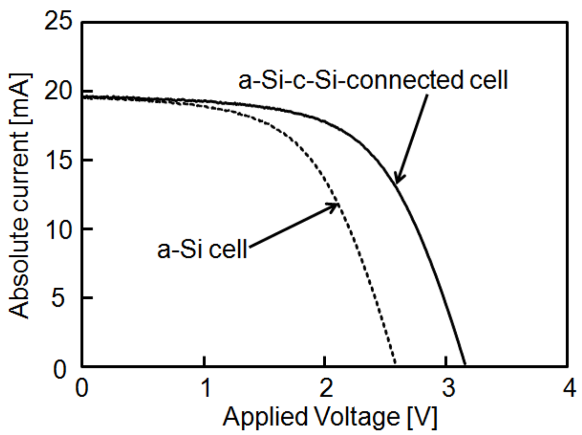


Fig. 5 Solar cell characteristic of a-Si and c-Si solar cells connected cell, as shown in Fig. 3. Dashed line is solar cell characteristic of a-Si solar cell for comparison.

No change in solar cell characteristic was observed as the a-Si filter was placed between the a-Si and c-Si solar cells. We interpret that the light lower wavelength than 700 nm was absorbed in the a-Si cell, while the light in the wavelength range from 700 to 1100 nm was contributed to power generation of c-Si solar cell. The light in the wavelength range from 700 to 1100 nm had about 50 % photon numbers of the total numbers of AM 1.5 from 380 to 1100 nm. This is a high enough illumination intensity for the c-Si solar cell to keep almost the V_{oc} condition and bias the partner a-Si solar cell at -0.55 V. The simple idea given in Fig. 3 and fundamental demonstration shown in Fig. 5 show a capability of utilizing solar light effectively to generate electrical power by cascade-type light absorption by each solar cell component.

Summary

We proposed multi-connected solar cells with different band gaps. A commercial three-serially connected a-Si solar cell was illuminated AM1.5 light at 1 sun with an incident angle of 60 degrees. The reflection light from the a-Si cell was illuminated to a commercial single c-Si solar cell facing the a-Si solar cell with a slant angle of 70 degrees. Two solar cells were serially connected using an electrical wire. The two combined solar cells gave V_{oc} of 3.2 V, while V_{oc} of the individual a-Si and c-Si solar cells gave of 2.6 and 0.55 V, respectively under the AM1.5 light illumination at 1 sun. The high V_{oc} was achieved by electrical power generation of the c-Si solar cell with illumination of reflection light with photon energy lower than the band gap energy of the a-Si solar cell. On the other hand, I_{sc} was limited to be 19 mA by that of a-Si solar cell, while the c-Si solar cell gave much higher I_{sc} of 0.22 A. The present result demonstrates effectively electrical power generation by simple configuration of multiple-connected solar cells with different band gap energy.

Acknowledgments
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