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Next-generation High Efficiency and Low Cost GaAs/Si Multijunction Solar Cells with Smart Stack Technology

Kikuo Makita[1], Hidenori Mizuno[1], Ryuji Oshima[1], Takeshi Tayagaki[1], Masaaki Baba[2], Noboru Yamada[2], Hidetaka Takato[1] and Takeyoshi Sugaya[1]

[1]National Institute of Advanced Industrial Science and Technology (AIST)
AIST Tsukuba, Central 2, Umezono 1-1-1, Tsukuba, Ibaraki, 305-8568, Japan
Phone: +81-29-861-3263, Fax: +81-29-861-5615, E-mail: kikuo-makita@aist.go.jp
[2]Nagaoka University of Technology, Japan

Abstract

Multi-junction (MJ) solar cells have a practical solution to consist with high efficiency and low cost. This paper shows the demonstrations of a GaAs/Si MJ solar cells with mechanical stacking method. Our key technology is the direct bonding using conductive nanoparticle alignment, which is named "Smart Stack" technology. Using this technology, we fabricated an InGaP/GaAs/Si 3-junction solar cell and observed the efficiency of 24.71% (AM1.5g). According to our theoretical prediction, these efficiencies can be improved over 30% under the optimized structure design. In addition, we examined the cost analysis of the GaAs/Si MJ module. Under the low concentration, the cost attains the competitive level (module cost with lens_ <0.4$/W). The obtained results show the possibility of GaAs/ Si MJ solar cells as next generation solar cell.

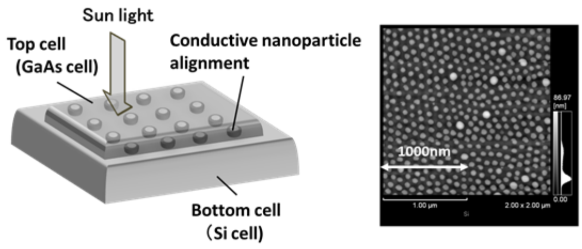
1. Introduction

The reduction of PV power generation cost is an important issue of global energy policy. According to "NEDO PV Challenges", the cost target of PV electricity at 2030 is 7 yen/kWh (<0.1 $/kWh). Therefore, the development of new solar cells having high efficiency and low cost becomes the urgent strategy. Against this background, multi-junction (MJ) solar cell is one of the possibility to achieve this target. The MJ solar cell has enabled very high efficiency over 30%. The MJ solar cells using mechanical stacking technology have been particularly interested as next generation solar cell [1, 2]. The mechanical stacking enables high efficiency and low-cost because of flexible and most appropriate combination of different cells. In here, GaAs//Si MJ solar cell is a powerful combination. GaAs-based cell essentially has high efficiency. Si cell has high sensitivity for long wavelength region and holds the promise of low cost bottom cell. According to our theoretical prediction, the GaAs//Si MJ solar cells have a potential to reach more than 30% efficiency.

In this paper, we shows the demonstrations of GaAs//Si MJ solar cells with mechanical stacking method. Our key technology is a powerful bonding method using a Pd nanoparticle alignment, which is named "Smart Stack" technology [3-7]. We realized an InGaP/GaAs/Si 3-junction solar cell with 24.71% [7].

2. Device Approach

Figure 1-(a) shows a conceptual diagram of the GaAs//Si MJ solar cell. Top GaAs-based cell of one or more than one junctions and Si bottom cell are connected. In here, our key technology is the semiconductor bonding with Smart Stack technology, which is the integration of conductive nanoparticle (Pd) alignments at the bonding interface. Pd nanoparticles were aligned on a bottom Si cell through the use of self-assembled block copolymer templates [3,6]. A top GaAs-based cell was separated from the growth substrate by Epitaxial Lift-off (ELO) technique[8]. Finally, two cells were stacked under the light load (5 N/cm^2). Figure 1-(b) shows the AFM image of a Pd nanoparticle alignment on a Si cell, with the domain size of 50 nm and interdomain distance of 100 nm. The concentration of the conductive domain was estimated to be 1×10^{10} cm^{-2}. The top-side cell and bottom-side cell are interconnected electrically (bonding resistance <1Ωcm^2) thorough the Pd nanoparticles with minimal interfacial optical loss (<2%).



(a) (b)

Fig. 1(a) Conceptual diagram of the GaAs//Si MJ solar cell with Smart Stack Technology. (b) AFM image of a Pd nanoparticle alignment on a Si cell.

Figure 2 shows the theoretical conversion efficiencies of the GaAs//Si 3-junction solar cell with respect to the band-gap energy (Eg) and quantum efficiency (QE) of the bottom cell. Top cell is restricted to be an InGaP/GaAs 2-junction cell. These values are calculated under 1 sun and ideal current matching conditions. In here, considering the best efficiency of Si solar cell (26.33%), it is difficult to achieve 30% only in a Si cell. On the other hand, the InGaP/GaAs//Si 3-junction solar cell is predicted to overcome 30% efficiency. The important issue is to raise the quantum efficiency of the Si cell beyond 0.85. After all, the overall performance is limited by the Si bottom cell, and the high-efficiency structure of Si cell, such as surface texturing, should be finally necessary.

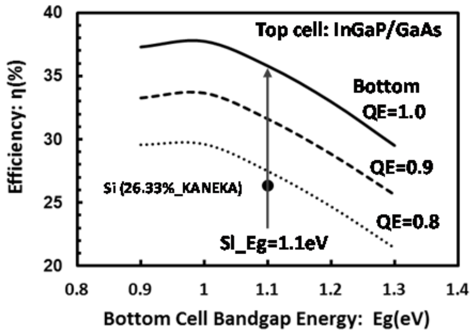


Fig. 2 Theoretical conversion efficiencies of the InGaP/GaAs//Si 3-junction solar cell.

3. Experiment and Discussion

Using Smart Stack Technology, an InGaP/GaAs/Si 3-junction solar cell were fabricated[7]. As the top cell, two-junction cell consisting of p-InGaP (Eg-1.89 eV) and p-GaAs (Eg-1.42 eV) absorption layers connected with a tunneling layer was used. As the bottom cell, the simplest and widely-used Si cell with Al-back surface field-type was used. Si (100) wafer was a single-side mirror polished with the thickness of 625 μm. Two cell are connected with Smart Stack technology.

Figure 3 shows the current-voltage characteristic under the simulated AM1.5G spectrum. It was revealed that the total efficiency (η) was 24.71% with open-circuit voltage (Voc), short-circuit current density (Jsc) and fill factor (FF) of 2.92 V, 10.60 mA/cm^2 and 0.80, respectively. Here, the efficiency was mainly limited by the photocurrent from the Si bottom cell. The efficiency can be further improved by optimizing the structure of each cell.

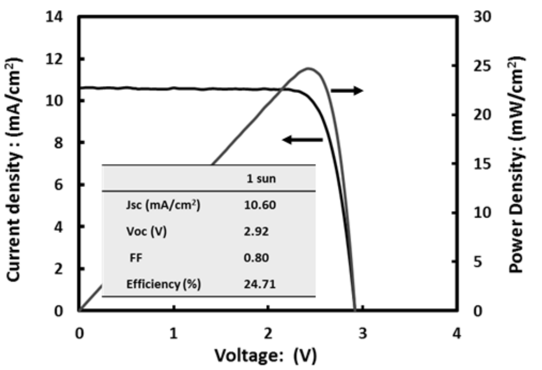


Fig. 3 Current-voltage characteristic of the InGaP/GaAs//Si 3-junction solar cell [7].

Finally, Fig. 4 shows our cost modelling for the InGaP/GaAs//Si module with Smart Stack technology. In this case, module efficiency is 30%, and GaAs substrate is re-used 10 times. GaAs growth method is assumed to be Hydride-VPE [9], which is low cost technique compared to general MOCVD. The basic cost is 0.9 $/W at 1 sun. However, this is not enough to achieve the cost target of <0.1 $/kWh. Therefore, we examine the application of the low concentration system which is a practical solution to consist with high efficiency and low cost. Concentrated solar is useful to push up conversion efficiency. The decrease of high expensive GaAs cell area contributes to cost reduction. Low concentration system does not require a tracking system. As shown in Fig. 4, under the low concentration, the cost drops drastically. The competitive cost level (module cost with lens_ <0.4$/W) can be realized at 6 suns.

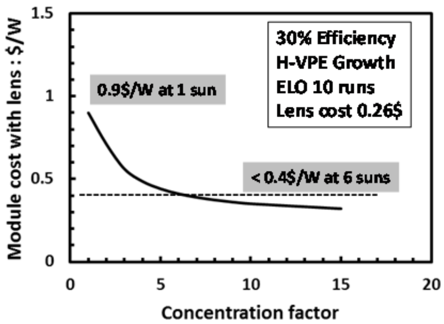


Fig. 4 Cost modeling for the InGaP/GaAs/Si 3-junction solar cell module with Smart Stack technology.

4. Conclusions

We fabricated the InGaP/GaAs/Si 3-junction solar cell with Smart Stack technology, and observed the maximum efficiency of 24.71% . According to our theoretical prediction, the efficiency can be improved over 30%. These results suggest that Smart Stack technology is promising to obtain high efficiency and low cost next generation solar cells. The improvement for device performance is currently ongoing in our group.

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