Feasibility study of two-terminal tandem solar cells integrated with smart stack, areal current matching, and low concentration

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ABSTRACT

The “SMAC module” is a low-cost, high-efficiency photovoltaic module that integrates three techniques: a “Smart stack,” “Areal current matching,” and “solar Concentration.” This paper presents the result of a proof of concept study of the SMAC module conducted using device simulations and indoor experiments. The simulation results show that an SMAC module with a two-terminal GaAs/Si tandem solar cell can achieve an efficiency of approximately 30% and superior electricity generation per unit top cell area. The performance of the GaAs/Si solar cell developed in this study is similar to that of a GaAs/InGaAsP solar cell under concentrated artificial sunlight and is consistent with the simulation results.

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KEYWORDS
multi-junction solar cells; III–V solar cells; silicon solar cells; mechanical stack; areal current matching; concentrator photovoltaic

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1. INTRODUCTION

State-of-the-art III–V multi-junction (MJ) solar cells have achieved high cell conversion efficiencies of more than 40% [1–5]. However, the use of III–V MJ cells in practical applications has been limited by their high manufacturing costs. Thus, cost reduction for III–V MJ solar cells is an important issue. III–V MJ solar cells are typically fabricated by metal organic vapor phase epitaxy (MOVPE), in which III–V subcells are grown monolithically on a lattice-matched but high-cost substrate such as Ge or GaAs. Si is an attractive substitute for the substrate in terms of its lower cost and bandgap suitability. Notable efforts have been made in the study of Si-based III–V MJ solar cells.

There are two major approaches to fabricating Si-based III–V MJ solar cells: epitaxial growth [6–11] and mechanical stacking [12–18]. In the epitaxial growth approach, the traditional MOVPE process can be used with minor modifications; however, lattice mismatch between Si substrates and III–Vs increases the difficulty of fabricating high-quality III–V MJ solar cells. The mechanical stacking approach is more flexible than the epitaxial growth approach with respect to the selection of the material set for MJ solar cells, although it requires a non-traditional fabrication process. This recently developed technique makes it possible to fabricate a mechanically stacked MJ solar cell in which each subcell can have a different lattice constant. By means of the mechanical stacking approach, III–Vs can be stacked on not only Si but also other low-cost materials, such as CuInGaSe (CIGS) [19].

The smart stack technique developed by AIST is an advanced mechanical stacking technique that uses metal...
nanoparticles, produces excellent optical and electrical properties, and enables flexible device design [19–23]. The smart stack technique uses the epitaxial lift-off (ELO) process to separate the device layers from the substrate [24–27], making it possible to reuse the substrate repeatedly. A recent cost analysis showed that the use of the ELO process in the fabrication of a dual-junction GaAs/Si cell leads to a significant cost reduction [28].

In the design of MJ solar cells, current matching among the series-connected subcells is also an important issue in obtaining high efficiency. In state-of-the-art MJ solar cells, the band gap of each subcell in a series connection is tuned so that the current generated by each subcell is at the same level under the standard solar spectrum. Recently, an areal current matching (ACM) technique has been proposed [16]. In this technique, an MJ cell consists of subcells that have different active areas, and the areas of the subcells can be varied independently to reduce the current mismatch. A similar concept called a “STEP solar cell” has also been mentioned in the literature [29,30]. The advantage of ACM in the fabrication of a mechanically stacked III–V/Si solar cell, in which the bottom Si cell has a slightly larger active cell area than the upper III–V subcells, has been experimentally demonstrated under 1-sun illumination [16].

Concentrator photovoltaics (CPV) is another approach to reducing the cost of a photovoltaic module with MJ solar cells. In this approach, an inexpensive concentrator concentrates sunlight on the solar cell, which can reduce the solar cell size and thus the cell cost. Various CPV systems with low and high concentration ratios have been developed and studied [31]. According to the theory of nonimaging concentrator optics, the acceptance angle of the concentrator decreases as the concentration ratio increases [32].

As mentioned above, mechanical stacking, ACM, and solar concentration are effective techniques for cost-effective production of III–V MJ photovoltaic modules. However, to date, few studies on the integration of these three techniques have been conducted. Recently, the authors introduced the concept of a “SMAC” MJ photovoltaic module that integrates a Smart stack, Areal current matching, and solar Concentration and have reported preliminary device simulations and cell fabrications of two-terminal (2T) GaAs/InGaAsP tandem solar cells [33]. This paper describes a further investigation of the feasibility of this concept in which solar cell performance was examined through updated device simulations and indoor experiments. In this study, a two-terminal (2T) GaAs/Si tandem solar cell was fabricated and compared with 2T GaAs/InGaAsP tandem solar cells.

### 2. SMAC MODULE CONCEPT

Figure 1 shows a conceptual image of the SMAC module. A high-efficiency solar cell, that is, the III–V top cell, is mechanically stacked on a low-cost bottom cell via the smart stack (SS) technique. Metal nanoparticles are formed at the interface between the top cell and bottom cell, based on copolymer-templated fabrication and van der Waals bonding, resulting in high optical transmission (optical loss < 2%) and low electrical contact resistance (<1 Ω cm²) [21,22]. With the ACM technique, the active cell area of the top cell is made smaller than that of the bottom cell, so that a portion of incident sunlight is directed to the bottom cell to achieve current matching between the stacked subcells in the 2T MJ solar cell. The concentrator optics are coupled on the 2T MJ solar cell to concentrate a portion of the sunlight onto the top cell, which contributes to reducing the top cell size. In this study, a low-concentration (LC) system was expected to be cost-effective because LC systems typically do not require a high-accuracy tracking system and a cooling device and because the concentrator’s shape accuracy and concentrator–cell alignment accuracy can be lower than in high-concentration systems. In this device geometry, the diffuse component of the sunlight usually lost in conventional concentrator systems can potentially be gainfully recovered by the bottom cell.

### 3. SIMULATION

The feasibility of the SMAC concept was examined by means of a device simulation based on semiconductor physics [34]. Figure 2 shows the simulation model. Figure 2(a) shows the electrical model of 2T tandem solar cell with ACM. The top and bottom cells are connected in series. The bottom cell has two components, the non-

![Figure 1](image-url)

**Figure 1.** Conceptual image of the SMAC module (SMart stack with Areal current matching and solar Concentration). [Colour figure can be viewed at wileyonlinelibrary.com]
stacked area that receives the sunlight directly and the stacked area, which are connected in parallel. Figure 2(b) shows the optical model, which consists of the concentrator optics (lens) and the solar cell. The sunlight incident on the lens aperture, $I_0 \text{[sun]}$, is uniform, and the level of irradiance is 1-sun. For simplicity, the irradiance distribution on the solar cell surface is assumed to follow a step pattern. The top cell surface receives higher irradiance $I_H \text{[sun]}$ and the "extra" bottom cell surface receives lower irradiance $I_L \text{[sun]}$. Assuming that the lens performs lossless concentration and that the lens aperture area $A_{\text{lens}}$ is identical to the bottom cell area $A_{\text{bottom}}$, the following relationship can be derived based on the energy conservation law:

\[
I_L = \frac{(I_0 \times A_{\text{bottom}} - I_H \times A_{\text{top}})}{(A_{\text{bottom}} - A_{\text{top}})}
\]

where $A_{\text{top}}$ and $A_{\text{bottom}}$ represent the top cell area and bottom cell area, respectively. When $I_H$ and $A_{\text{bottom}}/A_{\text{top}}$ ratio are given, $I_L$ can be determined. It should be noted that $I_H \leq A_{\text{bottom}}/A_{\text{top}}$ must be maintained. The ratio $A_{\text{bottom}}/A_{\text{top}}$ is equivalent to the geometric concentration ratio. The semiconductor device model used for the simulation is based on the following assumptions: (i) The properties of the semiconductor materials, such as the carrier lifetime and the cell performance for each of the subcells, are taken into account, as summarized in Table I [35]. (ii) The optical efficiency of the lens and the external quantum efficiency (EQE) of the solar cell are 100%. (iii) There is no loss of sunlight at the interface between the top cell and the bottom cell. (iv) The electrode resistance $R_E$ is negligible (0 $\Omega \cdot \text{cm}^2$) and the interfacial resistance $R_I$ is 1 $\Omega/\text{cm}^2$. (v) The cell temperature is 300 K.

The simulated current–voltage characteristics were evaluated using a performance factor defined as $P_{\text{max}}/A_{\text{top}}$, which is a measure of cost-effectiveness. $P_{\text{max}}$ is the maximum generated power of the 2T tandem solar cell. Because the solar cell in the SMAC module is supposed to consist of an expensive top cell and inexpensive bottom

| Material parameters          | GaAs  | InGaAsP | Si    |
|------------------------------|-------|---------|-------|
| Bandgap [eV]                 | $E_g$ | 1.42    | 1.15  | 1.12  |
| Effective mass of electron and hole — | $(m_n^*/m_0)$ | 0.063 | 0.069 | 0.98  |
|                             | $(m_p^*/m_0)$ | 0.51   | 0.55  | 0.49  |
| Lifetime of electron and hole [ns] | $\tau_n$ | 250    | 10*   | 30 000 |
|                             | $\tau_p$ | 3000   | 3000* | 10 000 |
| Mobility [cm$^2$/V s]       | $\mu_n$ | 8500   | 4300  | 1400  |
|                             | $\mu_p$ | 400    | 128   | 480   |

Subcell performance at 1-sun

|                     | GaAs  | InGaAsP | Si    |
|---------------------|-------|---------|-------|
| Short-circuit current [mA/cm$^2$] | $J_{sc}$ | 32.1    | 42.5  | 43.9  |
| Open-circuit voltage [V] | $V_{oc}$ | 1.02   | 0.731 | 0.647 |
| Fill factor [—]     | $FF$  | 0.89    | 0.85  | 0.84  |
| Efficiency [%]      | $\eta$ | 29.4    | 26.8  | 24.1  |

*Lifetime of the InP.
cell and lens, the dominant factor that influences the module cost is the top cell area.

Figure 3(a) shows the effect of the top cell irradiance $I_{th}$ on the performance factor $P_{\text{max}} / A_{\text{top}}$ for various $A_{\text{bottom}} / A_{\text{top}}$ ratios and a constant $A_{\text{top}}$ (0.16 cm$^2$). Each performance factor curve has a peak value at the optimal $I_{th}$ for each $A_{\text{bottom}} / A_{\text{top}}$ value, where the photogenerated current is matched between the top cell and the bottom cell. This means that the management of the irradiance distribution by low-concentration optics enhances the cost-effectiveness of the ACM-based 2T tandem solar cell remarkably. It should be noted that the open-circuit voltage increases slightly as $I_{th}$ increases. The efficiency, however, gradually decreases as $I_{th}$ increases because the resistive loss increases because of series resistances. For example, the efficiency reduces to half when the top cell irradiance increases from $I_{th} = 4$ to $I_{th} = 30$ in both solar cells. Thus, for the higher concentration, a reduction in the interfacial resistance is necessary.

Figure 3(b) shows a comparison of the peak value of the performance factor and the efficiency in the following three cases: (i) application of SS only with no concentration and no extra bottom cell area (termed the “SS-only” case); (ii) application of both SS and ACM but no concentration (termed the “SS + ACM” case); and (iii) application of all three techniques (termed the “SS + ACM + LC” case), that is, the SMAC module. The peak value was obtained at $I_{th} = 3.95$ for GaAs/InGaAsP and 4.10 for GaAs/Si in the case of $A_{\text{bottom}} / A_{\text{top}} = 6.0$. The SS + ACM and SS + ACM + LC cells achieved similar efficiencies of approximately 30%. The performance factor is however significantly maximized in the case of SS + ACM + LC because the top cell area is reduced by solar concentration.

For the GaAs/Si solar cell, the performance factor increased from SS + ACM to SS + ACM + LC by a factor of 3.93 and from SS to SS + ACM + LC by a factor of 10.13. This indicates that the combination of the ACM and LC techniques contributes to improving the cost-effectiveness of 2T tandem solar cells. In addition, the simulation results also indicate that the GaAs/Si solar cell achieved performance and efficiency similar to the GaAs/InGaAsP solar cell, meaning that changing the bottom material from III–Vs to Si does not diminish the performance and is thus a promising way to achieve cost reduction.

4. EXPERIMENT

4.1. A. Cell preparation

To verify the simulation results, an indoor experiment was conducted. 2T GaAs/InGaAsP and GaAs/Si tandem solar cells were fabricated using the SS technique developed by AIST [20,21]. Pd nanoparticle arrays were used for the stacking interface. As shown in Figures 4(a) and (b), the GaAs top cell consisted of a p-GaAs ($E_g = 1.42$ eV) absorption layer and an n-GaAs emitter layer. In the GaAs/InGaAsP cell, an InGaAsP bottom cell with a p-InGaAsP ($E_g = 1.15$ eV) absorption layer and an n-InGaAsP emitter layer was formed on an InP substrate. In the GaAs/Si cell, a Si bottom cell with a p-Si ($E_g = 1.12$ eV) absorption layer and an n-Si emitter layer was formed on a Si substrate. The band gaps of the subcells were designed to be the same as those used in the simulation. Figure 4(c) shows the fabricated 2T tandem solar cell. The electrode area of the top cell ($A_t$), the top cell area ($A_{\text{top}}$), the active top cell area ($A_{\text{top,act}}$), the bottom cell area ($A_{\text{bottom}}$), and the cell area ratio are shown in Figure 4. For both 2T solar cells, the bottom cell was expected to be the current-limiting cell under the uniform AM1.5G standard spectrum. The efficiency of each subcell was measured using an I–V tracer under a 1-sun AM1.5G standard spectrum. The measured cell efficiency of the GaAs top cells used in the experiment was in the range of 16%–18% (open-circuit voltage: $V_{oc} = 0.9$ V, short-circuit current density: $J_{sc} = 25$ mA/cm$^2$, fill factor: FF = 0.7–0.8). The measured cell efficiencies of the InGaAsP and Si bottom cells used in the experiment were in the ranges of 16%–18% ($V_{oc} = 0.65$ V, $J_{sc} = 34$ mA/cm$^2$, FF = 0.7–0.8) and 13%–15% ($V_{oc} = 0.6$ V, $J_{sc} = 35$ mA/cm$^2$, FF = 0.6–0.7), respectively.

The current–voltage characteristics of the fabricated 2T tandem solar cells were measured by an I–V tracer under 1-sun and AM1.5G uniform irradiation in the SS-only and SS + ACM cases. In the SS-only case, the current–voltage characteristics were measured with a mask blocking the
light onto the extra surface area (the non-stacked area) of the bottom cell. In the SS + ACM case, the current–voltage characteristics were measured without the mask. Figure 5 shows the measurement results. There were no concentrating optics for either case. The current density in the SS-only case was defined as the current divided by the \( A_{\text{top}} \). The current density in the SS + ACM case was defined as the current divided by the theoretical active bottom cell area at which the current of the bottom cell theoretically matches that of the top cell. The theoretical active bottom cell area was calculated from the measured current density of the fabricated bottom cell, that is, 33.69 mA/cm\(^2\) for the InGaAsP cell and 35.94 mA/cm\(^2\) for the Si cell. In Figure 5, the SS + ACM case corresponds to a higher current density than the SS-only case because of the ACM effect. For the GaAs/InGaAsP solar cell, the performance factor \( P_{\text{max}} / A_{\text{top}} \) values were 10.42 mW/cm\(^2\) and 21.73 mW/cm\(^2\) for the SS-only and SS + ACM cases, respectively. For the GaAs/Si solar cell, the performance factor values were 10.28 mW/cm\(^2\) and 22.78 mW/cm\(^2\) for the SS-only and SS + ACM cases, respectively. For both types of solar cells, the performance factor value for the SS + ACM case was approximately double that for the SS-only case, and the performance of the GaAs/Si cell was comparable to that of the GaAs/InGaAsP cell.
4.2. B. Experimental setup

Figure 6 shows the experimental setup, which consisted of a Fresnel lens as the concentrating optical lens, the fabricated tandem cell, artificial sunlight with a beam collimation angle of ±1.16°, and a cooling stage. To vary the irradiance distribution over the solar cell surface, the distance \( f \) between the cell and the lens was varied by a linear adjuster so that the spot size of the concentrated light was changed. A lens mask with a square hole was attached to the Fresnel lens surface. Three types of lens masks with different square hole sizes (6×6 mm\(^2\), 8×8 mm\(^2\), and 10×10 mm\(^2\)) were prepared to vary the concentration level. The irradiance at the top cell \( I_H \) was evaluated by the short-circuit current of the reference Si cell, calibrated under 1-sun irradiation. The reference Si cell was covered with the mask with the square hole whose size was the same as the top cell size. The performance of the tested 2T tandem cell was measured by an I–V tracer. The cell temperature was maintained at 20–25 °C in the cooling stage during the measurement. First, the lens mask and the reference Si cell were set, and \( I_H \) was evaluated for various \( f \) positions. Then, the reference cell was replaced by the tested 2T tandem cell, and the current–voltage curve was measured for the same \( f \) positions.

4.3. C. Results and Discussion

Figure 7(a) shows the measured performance factor values for various \( I_H \) and \( A_{\text{lens}}/A_{\text{top}} \) values corresponding to those in Figure 3(a). It should be noted that in the simulation, \( A_{\text{lens}} \) was identical to \( A_{\text{bottom}} \), whereas in the experiment, \( A_{\text{lens}} \) was not always identical to \( A_{\text{bottom}} \) but rather sometimes larger or smaller than \( A_{\text{bottom}} \), depending on the combination of the tested 2T solar cell and the lens mask. The experiment was repeated three times under the same conditions. Each plot shows the average value, and the error bar indicates the maximum and minimum values. The trend of the experimental results is fairly consistent with that of the simulation results. The performance factor values exhibit a peak at a certain \( I_H \) value for each \( A_{\text{lens}}/A_{\text{top}} \) case. In addition, it is obvious that higher \( A_{\text{lens}}/A_{\text{top}} \) values result in higher performance factor values.

Figure 7(b) shows a comparison corresponding to that shown in Figure 3(b). For the GaAs/InGaAsP cell, the highest performance factor value was 84.00 mW/cm\(^2\) in the SS + ACM + LC case, which was 8.06 and 3.86 times larger than the values in the SS-only and SS + ACM cases, respectively. For the GaAs/Si cell, the highest performance factor value was 81.58 mW/cm\(^2\) in the SS + ACM + LC case, which was 7.94 and 3.58 times larger than the values in the SS-only and SS + ACM cases, respectively. The efficiency in the SS + ACM case was higher than that in the SS-only case because of the contribution of the ACM. However, the efficiency in the SS + ACM + LC case was slightly lower than that in the SS + ACM case. A similar trend was observed in the simulation results shown in Figure 3(b); however, the efficiency drop observed in the experimental results was larger than that observed in the simulation results. A possible reason for this is the effect of the finite carrier diffusion length in the lateral direction in the bottom cell, which was not taken into account in the present model. The shorter carrier diffusion length...
can lead to a decrease in carrier collection probability; hence, improvement of the surface passivation layer to suppress surface recombination as well as the use of an efficient electrode design is necessary to enhance the carrier diffusion length in the bottom cell. Overall, the performance of the GaAs/Si cell was found to be similar to that of the GaAs/InGaAsP cell, and the SMAC module concept was found to significantly improve the performance factor. It should be noted that in the present study, the performance factor did not take into account the cost of the lens and the extended bottom cell because they were assumed to be inexpensive. These costs should be taken into account to obtain more accurate and objective results.

The measured characteristics were fairly consistent with the simulation results. The measured performance factor values were, however, smaller than the corresponding simulation values. The major factors in the differences are the cell efficiency of the GaAs top cell, the optical efficiency of the lens, and EQE. The measured cell efficiency of the GaAs top cell used in the experiment was in the range of 16%–18%, whereas the GaAs top cell efficiency was assumed to be 29.4% in the simulation. The current efficiency record for a single-junction GaAs cell is 28.8% ($V_{oc} = 1.222\,\text{V}, J_{sc} = 39.68\,\text{mA/cm}^2, FF = 0.865$) [5]. The optical efficiency of the lens is approximately 90%; the 10% efficiency loss reduces the amount of power generated. The fabricated tandem cell was not fully coated by an anti-reflection coating so that the electrode at the top cell surface could be exposed to the measurement probe, whereas the EQE was assumed to be 100% in the simulation. These losses can be reduced by improved cell design and fabrication.

5. CONCLUSIONS

The feasibility of the SMAC module concept was examined through device simulation and indoor experiments. The simulation results show that the integration of ACM and low concentration into a 2T tandem solar cell system significantly enhances the power generation achieved per top cell area. Utilizing the SMAC module concept, a 2T GaAs/Si tandem solar cell has the potential to achieve an efficiency of approximately 30% with a smaller top cell size than a conventional module. This potential efficiency is similar to that of a 2T GaAs/InGaAsP tandem solar cell. The simulation results were verified by indoor experiments conducted using fabricated 2T GaAs/Si and GaAs/InGaAsP tandem solar cells. In the experiments, the irradiance distribution at the 2T tandem cell surface was managed by a concentrator lens. The trends in the experimental results for the fabricated 2T tandem cells were fairly consistent with those of the simulation results, confirming the feasibility of the SMAC concept, although the measured performance was lower than that indicated by the simulation results because of the preliminary design of the fabricated solar cells. The main advantage of the SMAC module concept include the flexibility of the MJ cell structure design, which allows a combination of III–V top cells and low-cost bottom cells with a reduced top cell size, which seems to be a promising approach to producing low-cost, high-efficiency III–V MJ photovoltaic modules. Another advantage of the proposed concept is the intermediate concentration regime in which the diffuse component of the sunlight can be gainfully recovered by the bottom cell. The main disadvantage is the complexity of the design optimization of the cell structure and modularization, including the concentrator optics. Further research is needed to establish the methodology for the cell and module design for practical conditions. The effect of the diffuse component was not considered in the simulations and indoor experiments conducted in this study. In future work, a detailed model with a practical optical element design is necessary to simulate the effect of spectral cell illumination of the beam and diffuse component. Outdoor characterization of the SMAC module is also necessary to confirm the validity of the simulation model.

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