Reduction of bonding resistance of two-terminal III–V/Si tandem solar cells fabricated using smart-stack technology

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This paper describes a method that remarkably reduces the bonding resistance of mechanically stacked two-terminal GaAs/Si and InGaP/Si tandem solar cells, where the top and bottom cells are bonded using a Pd nanoparticle array. A transparent conductive oxide (TCO) layer, which partially covers the surface of the Si bottom cell below the electrodes of the III–V top cell, significantly enhances the fill factor (FF) and cell conversion efficiency. The partial TCO layer reduces the bonding resistance and thus, increases the FF and efficiency of InGaP/Si by factors of 1.20 and 1.11, respectively. Eventually, the efficiency exceeds 15%. Minimizing the optical losses at the bonding interfaces of the TCO layer is important in the fabrication of high-efficiency solar cells. To help facilitate this, the optical losses in the tandem solar cells are thoroughly characterized through optical simulations and experimental verifications. © 2017 The Japan Society of Applied Physics

1. Introduction

The III–V multijunction (MJ) solar cells composed of stacks of materials with different bandgaps can efficiently utilize the solar spectrum and achieve high conversion efficiencies.1–4 However, III–V MJ solar cells are expensive because they are fabricated using rare metals such as Ga and In. Thus, cost reduction is an important issue in III–V MJ solar-cell fabrication. A typical III–V solar cell is fabricated by crystal growth on an expensive substrate such as Ge or GaAs, by metal organic vapor phase epitaxy (MOVPE). Si, being an inexpensive and common semiconductor material, can be an attractive alternative for the III–V solar-cell substrate. Therefore, III–V/Si solar cells have attracted attention as low-cost high-efficiency solar cells.

Epitaxial growth by MOVPE is a common technology for fabricating Si-based III–V MJ solar cells. However, the differences between the thermal expansion coefficients and lattice coefficients of Si and III–V materials increase the difficulty of fabricating high-quality III–V solar cells on Si substrates through epitaxial growth. For the above reason, the efficiency of the III–V/Si MJ solar cells fabricated by epitaxial growth is ~20%.1,2,4–6 On the other hand, mechanical stacking can be used to fabricate III–V/Si solar cells easily, and the solar cells fabricated through mechanical stacking achieve high efficiencies, often exceeding 30%.7,6 The mechanical stacking methods are roughly classified into direct bonding methods9–13 and adhesion methods using transparent adhesives.12–15 Direct bonding requires the solar cell surface to be very flat, to bond. The adhesion method suffers from optical losses because of the opacity of the adhesive and reflection at the stacked interface. Therefore, to fabricate high-efficiency solar cells, the direct bonding method employs chemical mechanical polishing and the adhesion method uses advanced optical designs. The smart-stack technology developed by the Advanced Industrial Science and Technology (AIST) is a mechanical bonding technology that uses metal nanoparticles (NPs).16–18 This technology relaxes the flatness requirement of the solar cell surface, produces excellent optical and electrical properties, and enables flexible device designs. The smart-stack technology uses an epilaminal lift-off technology (ELO). The ELO is a technique of peeling the device layer of the III–V solar cell from the substrate by etching; the substrate remaining after peeling can be reused.19 In other words, the ELO can reduce the consumption of expensive rare metals by using the same substrate multiple times.

In this study, we focus on the bonding resistance of two-terminal (2T) GaAs/Si and InGaP/Si tandem solar cells fabricated using the smart-stack technology. The bonding resistance associated with the smart-stack technology is the sum of the contact resistances between each subcell and the metal NP, and the resistance of the metal NP. In the smart-stack technology, Pd, which has a low contact resistance to III–V materials, is used as the metal NP.20 However, the contact resistance between Pd and Si is higher than that between Pd and III–V materials. Thus, the III–V/Si solar cells fabricated by smart-stack technology have high bonding resistances. Therefore, an efficient method for the reduction of contact resistance is required. A possible solution for this issue is to coat the surface of the Si cell with a transparent conductive oxide (TCO) film;21–23 however, the TCO layer causes optical losses owing to the difference in refractive index between the top cell material and the TCO. A method to reduce the reflection losses of tandem solar cells using TCO has not yet been proposed. In this paper, first, to analyze the optical losses caused by the TCO layer, the reflectances of the III–V/Si tandem solar cells (GaAs/Si and InGaP/Si) with TCO are calculated through optical simulations. Then, the calculation results are verified using the experimental results. Finally, partial coating of the TCO layer is proposed as an effective solution to reduce the bonding resistance without increasing the optical losses. The performance after applying the partial TCO coating on the Si bottom cell surface is characterized for the fabricated tandem solar cells, through indoor experiments under standard test conditions (STCs), and is compared with that of the tandem solar cells with full...
TCO coating and those with no coating. The partial TCO structure for reducing reflection loss is a novel approach.

2. Optical simulation

In this study, In$_2$O$_3$–SnO$_2$ (ITO) was used as the TCO. The optical losses were calculated using the Fresnel equations, based on the refractive indexes of air, TiO$_2$, SiO$_2$, GaAs, InGaP, ITO, and Si. Figure 1 shows the simulation models of the simplified cell structures for the cases without ITO layer (w/o ITO) and with an ITO layer between the top and bottom cells (w/ ITO). In each structure, the reflectance was calculated for the cases where the top cell was GaAs and InGaP. The refractive indexes used are shown in Table I. The average refractive index in the bottom cell absorption wavelength range (GaAs/Si: 872–1107 nm, InGaP/Si: 652–1107 nm), where the sunlight components are to be transmitted through the top cell and absorbed by the Si bottom cell, was used for the simulations with the following assumptions: (1) The refractive index and absorption of the Pd NP layer were not considered, i.e., the Pd NP layer did not exist optically. (2) The absorption of each layer was zero. (3) Light was incident perpendicular to the model.

Figure 2 shows the simulated average reflectance of each structure for the bottom cell absorption wavelength range. In the GaAs/Si solar cell, the reflectances of the different structures w/o ITO and w/ ITO were 12.31 and 34.40%, respectively, in the wavelength range of 873–1107 nm. In the InGaP/Si solar cell, the reflectances of the different structures w/o ITO and w/ ITO were 11.58 and 30.72%, respectively, in the wavelength range of 652–1107 nm. The reflectance, i.e., the reflection loss, increased by approximately 20 points in both solar cells when the ITO layer was applied to the bonding interface. These results imply that applying a TCO layer that coats the entire surface of the bottom cell is not the best solution.

3. Solar cell characterization

3.1 Cell preparation

To verify the simulation results, 2T GaAs/Si and InGaP/Si tandem solar cells were fabricated using the smart-stack technology. Figure 3 shows the fabricated solar cells and their structures. Figure 3(a) shows a photograph of a GaAs/Si solar cell without ITO layer, and subcell sizes. (b) GaAs/Si and InGaP/Si cell structures without ITO layer. (c) ITO layer patterns for fabricated tandem solar cells: w/o ITO structure has no ITO layer, w/ ITO structure has ITO layer on the entire surface of the bottom cell, and partial ITO structure has ITO layer on a part of the stacked area so that the partial ITO coating is only under the electrodes of the top cell. (d) ITO coated area of the partial ITO structure.
in Table II. Figure 3(c) shows the three types of ITO layer structures examined in the experiment, i.e., w/o ITO, w/ ITO, and partial ITO. According to the simulation results, large reflections occur in the w/ ITO structure, although the ITO can lower the bonding resistance. To reduce this optical loss, the partial ITO structure was newly attempted as a possible solution, although reduction of the ITO coating area could increase the contact resistance. In the partial ITO structure, the top cell may not be flat; it may be curved slightly because of the inserted ITO layer. Thus, the gap between the top cell and the bottom cell at the stacked interface may vary three-dimensionally. As it is technically difficult to perform accurate optical simulations for such complicated structures, the partial ITO structure was not analyzed through simulations, but directly characterized through experiments. Figure 3(d) shows the ITO coated area of the partial ITO structure. The partial ITO coating was applied with a width of 0.3 mm from the edge of the top cell to the center, and most of the ITO layer was located under the electrodes at the perimeter of the top cell surface. In this configuration, the partial ITO does not reflect sunlight because the electrodes reflect the sunlight, contributing to low reflection losses. The partial ITO layer covered approximately 13% of the stacked interface. In the w/ ITO and partial ITO structures, the ITO layer was formed with 70 nm thickness on the bottom cell surface. Since the ITO layer was thicker than the Pd NP, the ITO layer could decrease the adhesiveness of the smart stack in the partial ITO structure. Thus, the ITO was not placed under the center portion of the top cell but was arranged along the edge of the top cell. For the InGaP/Si solar cell, we fabricated w/o ITO and partial ITO structures; however, we did not fabricate a w/ ITO structure.

### 3.2 Experiment for reflectance measurement

The reflectance of the stacked area was measured to assess the optical losses caused by the ITO layer. Figure 4 shows the experimental setup for reflectance measurement, which consists of a halogen lamp, spectrometer, fiber optical cables, and the fabricated tandem solar cell. The light source fibers and single-detection fiber probe (6-around-1 fiber bundle design) were bundled to the fiber optical cables and connected to the halogen lamp and spectrometer, respectively. For the GaAs/Si solar cell, the reflectance was measured in the wavelength range of 700–1100 nm, including the bottom cell absorption wavelengths and a part of the top cell absorption wavelengths. For the InGaP/Si solar cell, considering the spectral characteristics of the light source, the measurement wavelength range was limited to 500–900 nm to maintain measurement accuracy. The diameter of the light spot (measuring area) was approximately 3 mm, and the light was incident only on the stacked area of each 2T tandem solar cell. It should be noted that the measured reflection includes the reflection from the electrodes (Au) at the top cell surface also.

![Figure 4](image-url) (Color online) Experimental setup for reflectance measurement.

![Figure 5](image-url) (Color online) Experimental results of the reflectance. (a) GaAs/Si solar cell reflectance for different structures. (b) InGaP/Si solar cell reflectance for different structures. (c) Average reflectance of the bottom cell absorption wavelength for different solar cells and structures.

Figure 5 shows the measured reflectance for various wavelengths. Figure 5(a) shows the reflectance of each structure of the GaAs/Si solar cell. Fluctuations in the reflectance for the absorption wavelengths of the bottom cell (873–1107 nm) were caused by interferences from multiple reflections between the SiO₂ surface and the bottom cell surface.
Table III. Summary of performances of different solar cells and structures.

| Material       | Structure | $J_{sc}$ (mA/cm²) | $V_{oc}$ (V) | FF | η (%) | $R$ (Ω·cm²) |
|----------------|-----------|-------------------|--------------|----|-------|-------------|
| GaAs/Si        | w/o ITO   | 15.64             | 1.44         | 0.57 | 12.89 | 20.1        |
|                | Partial ITO | 11.84             | 1.38         | 0.67 | 11.04 | 11.6        |
|                | w/ ITO    | 15.23             | 1.44         | 0.69 | 15.18 | 12.6        |
| InGaP/Si       | w/o ITO   | 13.59             | 1.66         | 0.60 | 13.54 | 64.9        |
|                | Partial ITO | 12.63             | 1.65         | 0.72 | 15.06 | 15.2        |

Figure 5(b) shows the reflectance of each structure of the InGaP/Si solar cell; interference due to multiple reflections occurred, similar to the GaAs/Si solar cells, at the absorption wavelengths of the bottom cell (652–1107 nm). Figure 5(c) shows the average reflectance for the bottom cell absorption wavelengths for different solar cells and structures. The w/o ITO and w/ ITO solar-cell structures showed good agreement with the optical simulation results, and it was revealed that, in both solar cells, the partial ITO structure showed approximately the same reflectance level as the w/o ITO structure, whereas, the solar cell with a full ITO layer covering the stacked interface showed large reflection. In the GaAs/Si solar cell, the average reflectances of the different structures w/o ITO and w/ ITO were 11.98 and 34.37%, respectively, which were almost the same values as those obtained from the simulations. The reflectance of the partial ITO structure was 14.18%. In the InGaP/Si solar cell, the reflectances of the different structures w/o ITO and with partial ITO were 16.27 and 14.82%, respectively.

3.3 Experiment for solar cell performance measurement

To evaluate the influence of the ITO layer on the bonding resistance, the current–voltage (I–V) curves of the fabricated 2T GaAs/Si and InGaP/Si tandem solar cells were measured under STC. Figure 6 shows the I–V curves of the fabricated solar cells with different structures. The measured $J_{sc}$, $V_{oc}$, FF, and η, and the series resistance $R$ calculated from the I–V curves are summarized in Table III.

During the I–V measurements, masks were used to regulate the active areas (power generation areas) of the solar cell. For the GaAs/Si solar cell, if the GaAs subcell area was identical to the Si subcell area, the current was remarkably limited by the Si subcell. To avoid this current mismatch, the areal current matching (ACM) technique was employed. In ACM, each subcell has a different active area, which can be changed to minimize the current mismatch. The ACM condition was achieved when the ratio of the active area of the Si subcell to that of the GaAs subcell was 1.38; the I–V curves were measured using a mask with an aperture area suitable to achieve this ratio. On the other hand, for the InGaP/Si solar cell, if the InGaP subcell area was identical to the Si subcell area, the current was slightly limited by the InGaP subcell; thus, the I–V curves were measured using a mask with an aperture area identical to that of the InGaP subcell area.

As a result, in both tandem solar cells, partial ITO structures showed the highest FF and efficiency; the FF increased by 0.12 points compared to the w/o ITO structure and the efficiency was greater than 15%. The ITO layer remarkably reduced the bonding resistance and the partial ITO structure had lower $R$ than the w/o ITO structure. The $J_{sc}$ trends agreed well with the optical simulation results. The $J_{sc}$ of the w/o ITO and partial ITO structures showed almost the same value for both solar cells, indicating that the partial ITO structure had low optical losses.

In the GaAs/Si solar cells, the $J_{sc}$ of the partial ITO structure was 2.62% lower than that of the w/o ITO structure, while the $J_{sc}$ of the w/ ITO structure was 24.30% lower than that of the w/o ITO structure. The $η$ of the w/ ITO structure was 11.04%, which was lower than that of the w/o ITO structure (12.89%). The $R$ of the w/ ITO and partial ITO structures showed approximately the same value, which was 7.5–8.5 Ω·cm² lower than that of the w/o ITO structure.

In the InGaP/Si solar cells, the $J_{sc}$ of the partial ITO structure was 7.06% lower than that of the w/o ITO structure, whereas, in the reflectance measurement, the partial ITO showed slightly lower reflectance than the w/o ITO structure. This difference may be caused by the difference in the external quantum efficiencies of the top cells in each structure. The $R$ of the partial ITO structure exhibited a value 49.7 Ω·cm² lower than that of the w/o ITO structure.

The effect of using the mask should also be discussed here. Because the active areas of the fabricated solar cells were regulated by the aperture sizes of the masks, nonactive areas were present in the solar cells, which were not exposed to...
light. These nonactive areas could cause a decrease in the $V_{oc}$ because of the aggravation of irradiance uniformity. In fact, without the mask, the measured $V_{oc}$ of the fabricated GaAs/Si and InGaP/Si solar cells were approximately 1.5 and 1.8 V, respectively; whereas, with the mask, the $V_{oc}$ decreased as shown in Table III. Preparing the right-sized solar cell could increase the $V_{oc}$ and potentially increase $\eta$ up to $\sim$16%. However, even after considering this potential improvement, the $FF$ and $\eta$ of the present solar cells are still at low levels. III–V/Si solar cells with $FF$ of 0.8 or more have recently been reported.\textsuperscript{1,9,23} Obviously, the $FF$s of the subcells used in our experiment were relatively low and will be improved in future studies.

4. Conclusions

To reduce the bonding resistances of the two-terminal III–V/Si tandem solar cells mechanically stacked by Pd nanoparticle array-mediated semiconductor bonding (termed as the smart-stack technology), we proposed a solar cell with an ITO layer at the stacked interface, evaluated the optical losses, and measured the $I$–$V$ curves under STC. Optical simulations and experiments revealed that approximately 20% of the reflection losses occurred in the solar cell with an ITO layer at the stacked interface, because of the difference in the refractive index between the top cell and the ITO layer. Based on the results of the optical simulation, a structure using a partial ITO layer and realizing low reflection, was designed and examined. A solar cell with the partial ITO layer structure was fabricated using the smart-stack technology, and was evaluated under STC. The $FF$ was found to be improved greatly, without decreasing the $J_{sc}$, and the $\eta$ increased up to 15% in both GaAs/Si and InGaP/Si tandem solar cells. The partial ITO layer remarkably reduced the bonding resistance. As a result, the series resistance of the GaAs/Si and InGaP/Si tandem solar cells with partial ITO layers decreased from 20–65 to 11–15 $\Omega$·cm$^2$. Although it will be difficult to apply the proposed method to solar cells stacked by a bonding method requiring a very flat surface, such as the direct bonding method, it can be applied to solar cells stacked using adhesive methods. The advantages of the proposed method are emphasized when the current density in the stacked area is increased by the concentration of sunlight and by using an ACM technique, where the influence of the bonding resistance becomes more significant.

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