Measurements of Potentials at Tap Contacts and Estimation of Resistance across Bonding Interfaces in InGaP/GaAs/Si Hybrid Triple-Junction Cells

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***Abstract*—InGaP/GaAs/Si hybrid triple-junction (3J) cells equipped with tap contacts are fabricated. The difference in potentials between bases of GaAs middle cells and emitters of Si bottom cells is measured while the 3J cells are illuminated. The resistance across the p-GaAs/n-Si bonding interfaces is estimated to be $\sim 4\ \Omega\mathrm{cm}^2$, which is 30 times higher than the resistance measured for interfaces of heavily-doped p-GaAs and n-Si substrates. Such high resistances in bonding interfaces in the 3J cells are likely to be attributed to their thin (several-nm-thick) n^+-Si emitters that also work as bonding layers.**

I. Introduction

InGaP/GaAs/Si triple-junction (3J) cells are promising candidates for high-efficiency and low-cost photovoltaics from the practical viewpoints [1]. Due to the difficulties in the epitaxial growth of III-V layers on Si substrates, such multi-junction cells are mostly fabricated by using surface-activated bonding (SAB) technologies [2], or using hybrid approaches. In the SAB process, the sample surfaces are cleaned prior to bonding by using fast atom beams of noble gas species such as Ar.

Although the electrical properties of bonding interfaces might be deteriorated by damages due to the Ar beam irradiation [3], preparatory studies with doped semiconductor substrates revealed that the resistance across the bonding interfaces is decreased to practically-applicable values by increasing concentrations of impurities in bonding layers [4] or by annealing the bonding interfaces [5]. Actually we previously achieved p^+-GaAs substrate/n^+-Si substrate junctions with an interface resistance of $0.13\ \Omega\mathrm{cm}^2$ [4]. The resistance across the bonding interfaces in actual hybrid multi-junction cells, however, have not yet been fully investigated although such resistance could contribute to the series resistance (R_s) in hybrid multi-junction cells. In this work, we directly measure potentials at bases of GaAs middle cells and emitters of Si bottom cells, or those at bonding layers, in hybrid 3J cells with additional tap contacts and estimate the resistance across the bonding interfaces.

II. Experiments

Si-based bottom cell structures were fabricated by the implantation of phosphor (P) and boron (B) ions and the rapid thermal annealing. The dose of P atoms for forming emitters was $4.3 \times 10^{14}\ \mathrm{cm}^{-2}$. The thickness and sheet resistance of emitter layers were estimated to be several nm and $\approx 800\ \Omega/\mathrm{sq.}$ by SIMS and TLM measurements, respectively.

We separately prepared heterostructures for InGaP/GaAs double-junction (2J) cells by the epitaxial growth on GaAs substrates. We fabricated n-on-p InGaP/GaAs/Si 3J cells with a nominal top-cell mesa area of 0.041 cm^2 (2.02 mm by 2.02 mm) by surface activation bonding (SAB) of the heterostructures and Si-based bottom cells and using the conventional device process. We formed tap contacts on bases of GaAs middle cells and emitters of Si bottom cells. The other steps for fabricating cells were the same as previous reports. The schematic cross section of 3J cells is shown in Fig. 1. It is notable that a part of the surface of Si bottom cells is exposed to the air so that their effective area is larger than that of top cells. The area of p-GaAs/n-Si bonding interfaces is 0.046 cm^2.

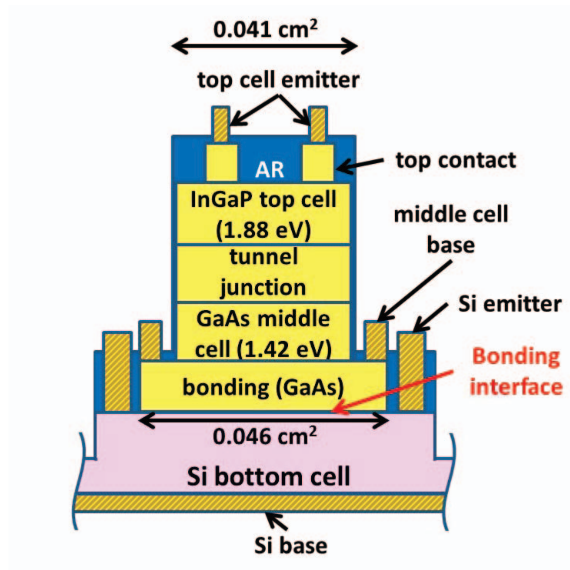

Fig. 1. A schematic cross section of 2.02-mm-by-2.02-mm InGaP/GaAs/Si 3J cells with tap contacts.

The current-voltage ($I-V$) characteristics of the 3J cell illuminated under the air mass 1.5G/one sun condition are shown in Fig. 2. The $I-V$ characteristics of the InGaP/GaAs 2J sub cell and those of the Si bottom cell, which were measured by using tap contacts, are also shown in this figure. The open-circuit voltage (V_{OC}) of the 3J cell (2.84 V) almost agreed with the sum of V_{OC} of the 2J sub cell (2.31 V) and Si bottom cell (0.49 V), i.e., the additivity of V_{OC} was confirmed. The short-circuit current (I_{SC}), maximum output power (P_{max}), resistance at the open-circuit-voltage condition ($-dV/dI|_{V=V_{\mathrm{OC}}}$) of the 3J cell are 0.448 mA, 1.041 mW, and 464 Ω, respectively. We normalized the achieved I_{SC} and P_{max} by the area of top cells and obtained the short-circuit current density of ≈ 11 mA/cm^2 and the conversion

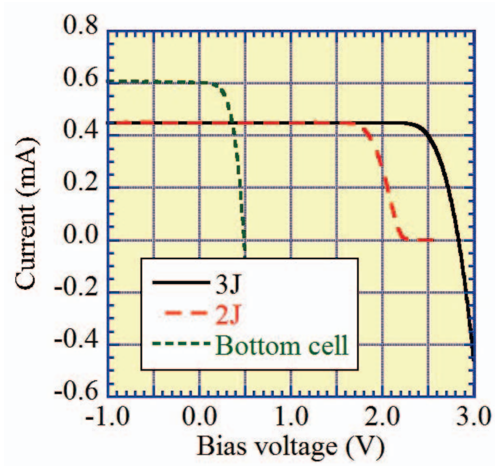

Fig. 2. $I-V$ characteristics of InGaP/GaAs/Si 3J cells, InGaP/GaAs 2J sub cells, and Si bottom cells illuminated under the condition of air mass of 1.5G and one sun.

efficiency of 25.5%, which are larger than our previous report [1]. In addition, I_{SC} of the Si bottom cell (0.601 mA) is larger than that of the 2J sub cell (0.447 mA). These results are attributable to uncovered parts of surfaces of the Si bottom cell. We also find that the series resistance for the 2J sub cell is higher than that for the 3J cell from Fig. 2, which is due to a large resistance at the tap contact on the GaAs base.

Potentials at the two tap contacts were measured while the 3J cell was illuminated and bias voltages were applied. The base of the 3J cell was grounded during measurements. The dependencies of the potentials at tap contacts and the current across the 3J cell on the potential at the emitter of 3J cell, or the bias voltage, are shown in Fig. 3(a). The oscillation in the potential at the contact on the GaAs base is likely to be due to the high contact resistance. V_{OC} of the 3J cell, 2J sub cell, and Si bottom cell was ≈ 2.78, 2.3, and 0.48 V, respectively. A slight discrepancy between these V_{OC} values and the results shown in Fig. 2 might be due to the difference in conditions for measurements.

Figure 3(b) gives the relationship between the difference in potentials at the tap contacts, which should be the bias voltage applied to the bonding interfaces, and the current in the 3J cell. The resistance across the bonding interface $R_{bonding}$ was estimated to be 89 Ω from the slope of the curve obtained by the least-square fitting. We measured potentials at tap contacts in 1.02-mm-by-1.02-mm 3J cells by using the same method. We found that the resistance was 386 Ω for bonding interfaces with an area of 0.013 cm^2, as is also shown in Fig. 3(b) .

III. Discussions

The difference between the slope of $I-V$ characteristics at the open-circuit voltage ($-dV/dI|_{V=V_{\mathrm{OC}}}$) and the estimated resistance at the bonding interface, which is $464-89=375\ \Omega$ for the 2.02-mm-by-2.02-mm 3J cell, is likely to be attributed to the diode resistance, the substrate (bulk) resistance, and the contact resistances. Based on the scheme of differential

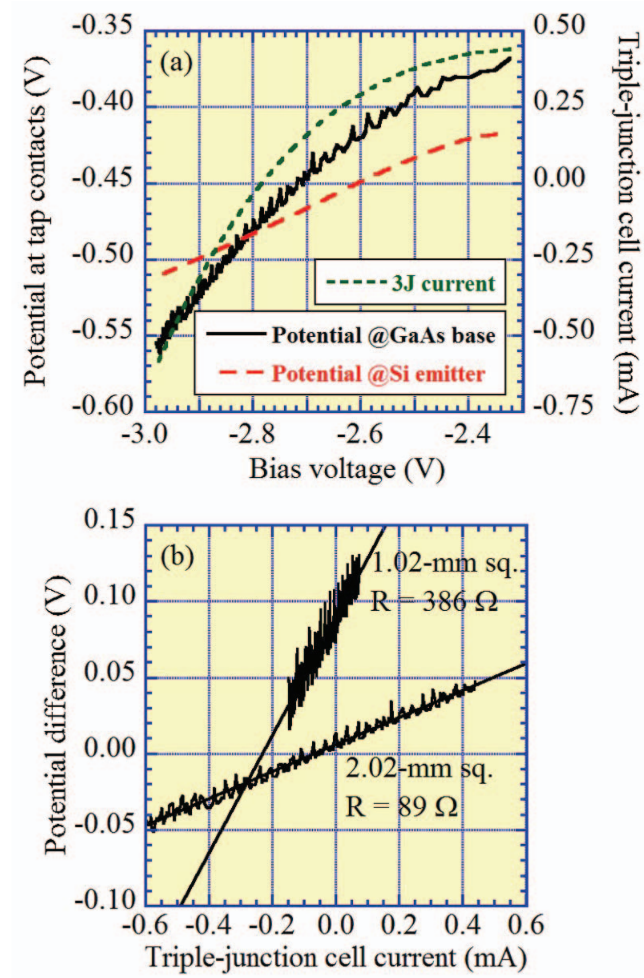

Fig. 3. (a) The dependencies of the potentials at the base of GaAs middle cell and the emitter of Si bottom cell and the current across the 2.02-mm-by-2.02-mm 3J cell on the bias voltage. (b) The relationships between the difference between bases of middle cells and emitters of bottom cells and the 3J-cell current for the 2.02-mm-by-2.02-mm and 1.02-mm-by-1.02-mm 3J cells. The results of least-square fitting to straight lines and the estimated resistances across the bonding interfaces are also shown.

resistance of p–n diodes, the diode resistance is approximately given by

$$(n_1+n_2+n_3)k_BT/(qI_{\mathrm{SC}}) = 3\times nk_BT/(qI_{\mathrm{SC}}), \quad (1)$$

where k_BT/q is the thermal voltage (25.9 mV at $T=300$ K) and n_1, n_2, and n_3 are the ideality factors of the respective sub cells. The right-hand side in the above equation is based on the assumption that the ideality factors of the respective sub cells are equal to n. Ignoring the contribution of the substrate resistance and the contact resistance, we obtained

$$3\times nk_BT/(qI_{\mathrm{SC}}) = 375\ \Omega, \quad (2)$$

which corresponded to $n=2.2$. This value was likely to disagree with the requirement of the physics of $p-n$ diodes that $n\leq 2$. The disagreement might be due to the resistances that we ignore. Similar analyses were performed for the 1.02-mm-by-1.02-mm 3J cell so that we obtained $n=1.9$.

The estimated resistances across the bonding interfaces corresponded to $\sim 4\ \Omega\mathrm{cm}^2$ for both 1.02-mm-by-1.02-mm and 2.02-mm-by-2.02-mm 3J cells, which was approximately 30 times higher than a previously-reported resistance for junctions made of p^+-GaAs and n^+-Si substrates. The discrepancy was likely to be due to thin (several-nm thick) n^+-Si emitter layers in bottom cells. The obtained results suggested that emitter structures in bottom cells should be revised for achieving bonding interfaces with lower resistances in 3J hybrid tandem cells.

IV. Conclusion

The resistance across the p-GaAs/n-Si bonding interfaces in InGaP/GaAs/Si 3J hybrid tandem cells were estimated by measuring potentials at tap contacts on bases of GaAs middle cells and emitters of Si bottom cells. The resistance amounted to $\sim 4\ \Omega\mathrm{cm}^2$, which was several ten times higher than that observed for junctions of heavily-doped substrates. Such high resistance in the bonding interfaces of 3J cells was likely to be attributed to thin n^+ emitter layers of bottom cells.

Acknowledgment

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