Surface-activating-bonding-based low-resistance Si/III-V junctions

J. Liang, S. Nishida, M. Morimoto and N. Shigekawa

The electrical properties of pn junctions, with various semiconductor materials with different doping concentrations fabricated by using surface-activated-bonding (SAB), were investigated by measuring their current-voltage (*I-V*) characteristics. The *I-V* characteristics of p^+-GaAs/n^{++}-Si, p^+-GaAs/n^+-Si, p^+-Si/n^+-Si, p^{++}-Si/n^+-InGaP, and p^+-Si/n^+-InGaP junctions showed ohmic-like properties. The interface resistance and the resultant electrical loss decreased with increasing impurity concentration at the interface. These results demonstrate the significance of SAB for fabricating tandem solar cells.

Introduction: Compound-semiconductor-based tandem solar cells, which have reportedly produced high conversion efficiencies in comparison with other solar cell structures [1], are promising as practical candidates for next-generation solar cells. Tandem cell structures with optimal band-gaps sequence, however, cannot be achieved by using epitaxial growth (monolithic tandem approach) because of the difficulties in the epitaxial growth due to lattice mismatching. The other approach, or hybrid tandem approach, is free from such difficulties and is likely to be promising for achieving high conversion efficiencies. The tandem solar cells [2–4] are likely to be fabricated by using the surface-activated bonding (SAB), in which the native oxide layers formed on surfaces of substrates are removed by Ar beam irradiation prior to bonding [5, 6]. The reduction of the electrical resistance across the *pn* junctions connecting the sub-cells is very important for realising high-efficiency hybrid tandem cells by using SAB.

In this Letter, *pn* junctions were fabricated with a variety of semiconductor materials and different doping concentrations by SAB. We characterised their electrical properties by *I-V* measurements and evaluated the relationship between the electrical properties and the impurity concentrations.

Experiments: We used 12 kinds of substrates for the SAB experiments. Their carrier concentrations are shown in Table 1. After the two substrates were bonded to each other by using SAB [5, 6], Al/Ni/Au (Ti/Au) multilayers were evaporated on the bottom surfaces of *p*-Si (*n*-Si) substrates, and then annealed at 400°C for 60 s so that *p*-Si/*n*-Si junctions were achieved. AuZn/Ti/Au multilayers were evaporated on the bottom surfaces of *p*-GaAs and *p*-InGaP substrates. AuGe/Ni/Ti/Au multilayers were evaporated on the bottom surfaces of *n*-InGaP substrates. All the samples were diced into 4 mm^2 pieces. *I-V* measurements were performed using an Agilent B2902A Precision Measurement Unit at room temperature. We subtracted the contribution of parasitic resistance from the measured *I-V* characteristics. The achieved characteristics are assumed to correspond to the intrinsic electrical properties of the junction.

Table 1: Carrier concentration of substrates

No.	Type	Carrier concentration cm^{-3}
1	p-Si(100)[a]	1.4×10^{15}
2	p-Si(100)[a]	2.4×10^{17}
3	p-Si(100)[a]	8.7×10^{18}
4	p^+-Si(100)[a]	2.6×10^{19}
5	P^{++}-Si(100)[b]	$\sim 1.5 \times 10^{20}$
6	P^+-GaAs(100)[c]	$\sim 1 \times 10^{19}$
7	p-InGaP(100)[c]	$\sim 1 \times 10^{18}$
8	n-Si(100)[a]	4.8×10^{16}
9	n^+-Si(100)[a]	2.6×10^{19}
10	n^{++}-Si(100)[b]	$\sim 6 \times 10^{19}$
11	n-InGaP(100)[c]	$\sim 1 \times 10^{18}$
12	n^+-InGaP(100)[c]	$\sim 1 \times 10^{19}$

[a]The carrier concentrations of substrates were estimated by Hall measurements at room temperature
[b]Boron and phosphorus ions were implanted for *p*-Si and *n*-Si substrates, respectively, at energy of 10 keV
[c]Epitaxial substrates

We also estimated the electrical loss due to the resistance across the junction in two-junction tandem cells with Si-based bottom cells in the following process. We assumed that the short-circuit current (J_{SC}) of the two-junction tandem cells, which is likely to be half of J_{SC} in single junction Si cells (ideally 44 mA/cm^2, under AM1.5 G, one sun conditions), should be 22 mA/cm^2. The loss due to the junction was defined as the product of 22 mA/cm^2 and the voltage drop for this current density value.

Results: Fig. 1 shows the *I-V* characteristics of p^+-GaAs(No. 6 in Table 1)/n^{++}-Si(10), p^+-GaAs(6)/n^+-Si(9), p^+-Si(4)/n^+-Si(9), p^{++}-Si (5)/n^+-InGaP(12), and p^+-Si(4)/n^+-InGaP(12) junctions measured between −0.1 and 0.1 V at room temperature. We found that the *I-V* characteristics shown in this Figure revealed ohmic-like properties. We obtained that the interface resistance was 0.13, 0.21, 0.54, 2.4, and 3.7 Ω·cm^2 for p^+-GaAs/n^{++}-Si, p^+-GaAs/n^+-Si, p^+-Si/n^+-Si, p^{++}-Si/n^+-InGaP, and p^+-Si/n^+-InGaP junctions, respectively, by least-square fitting around 0 V. The p^+-GaAs/n^{++}-Si junction brought about the smallest value of interface resistance in all the samples.

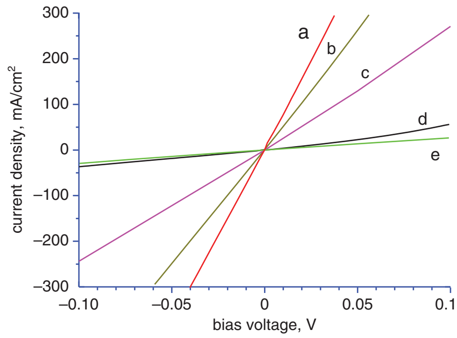

Fig. 1 *I-V characteristics of (a) p^+-GaAs/n^{++}-Si; (b) p^+-GaAs/n^+-Si; (c) p^+-Si/n^+-Si; (d) p^{++}-Si/n^+-InGaP; and (e) p^+-Si/n^+-InGaP junctions measured at room temperature*

The relationship between the loss across the pn junctions and the effective impurity concentrations $N^*(=N_A \times N_D/(N_A + N_D))$, where N_A and N_D are the acceptor and the donor concentrations, respectively, is shown in Fig. 2. Note that the depletion layer thickness in pn homojunctions is inversely proportional to $\sqrt{N^*}$. It can be seen that the loss is significantly reduced by increasing N^*. The lowest loss (0.063 mV/cm^2, which corresponds to the degradation in conversion efficiency of 0.063%) was observed for p^+-GaAs/n^{++}-Si junction. The lower loss in the *p*-GaAs/*n*-Si junction in comparison with that in *p*-Si/*n*-Si junctions with similar N^* might be attributable to the type-II band line-up in GaAs/Si junctions [6]. These results suggest that SAB is applicable for connecting sub-cells of the tandem solar cells with negligibly low junction resistance.

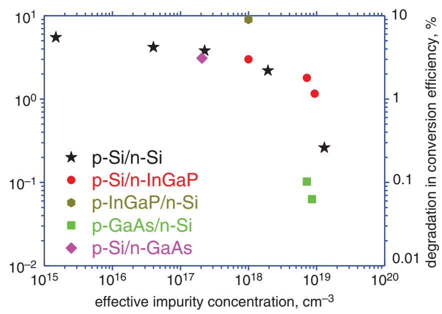

Fig. 2 *Power loss and degradation in conversion efficiency against effective impurity concentrations in p-Si/n-Si, p-Si/n-InGaP, p-InGaP/n-Si, p-GaAs/n-Si, and p-Si/n-GaAs junctions*

Conclusions: We fabricated pn junctions with various semiconductor materials by using SAB. The current-voltage characteristics of high-doped junctions showed ohmic properties. The loss across junctions are significantly reduced by increasing the effective impurity concentrations. A loss of 0.063 mW/cm^2 was estimated for the p^+-GaAs/n^{++}-Si junction. These results suggest the potentiality of the SAB method for fabricating hybrid tandem cells.

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One or more of the Figures in this Letter are available in colour online.

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