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Surface-Activated-Bonding Based InGaP-on-Si Double Junction Cells

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Abstract

We fabricated InGaP-on-Si double junction solar cells by using surface activated bonding (SAB). Their open circuit voltage was almost equal to those of the respective subcells. The efficiency of the double junction cells was enhanced in comparison with those of the subcells. These results suggest that high efficiency multi junction cells on Si can be fabricated by using SAB.

1. Introduction

The research and development of solar cells with high efficiencies is globally in progress. Multi junction cells composed of III-V material (InGaP, GaAs, InGaAs) based subcells have reportedly brought about the highest efficiency among a variety of solar cell structures [1]. Efficiencies higher than 30% were previously reported [2].

So as to increase the efficiency of multi junction cells, the number of subcells must be increased while their bandgaps fulfill the current matching condition. In addition, from the practical viewpoints, the bottom cells, which in most cases are made of Ge, should be preferably replaced by Si-based cells. These two requirements have led us to the contention that methods for piling up subcells with specific bandgaps on Si are needed. Given that the growth of III-V materials with a variety of bandgaps, hence different lattice constants and thermal expansion coefficients, on Si is still hard technical issues, hybrid approaches such as wafer bonding are assumed to be promising for realizing such advanced versions of multi junction cells.

We have been exploring the possibility of fabricating multi junction cells by bonding subcells using surface activated bonding (SAB) [3]. The surface of bonded samples was activated by means of the Ar plasma prior to bonding in the SAB, so that materials dissimilar to each other can be bonded without heating. We had previously reported the electrical characteristics of SAB-based Si/Si, III-V (GaAs, GaN)/Si junctions [4,5]. Noticeably we had confirmed that the SAB-based interfaces between heavily-doped GaAs and Si revealed excellent conductive properties [6]. In this paper, we report on fabrication of InGaP-on-Si double junction cells using SAB and their characteristics.

2. Results and Discussions

Cell fabrication

We obtained the lattice-matched *n*-on-*p* InGaP top cell structures on (100) GaAs substrates by growing a 300-nm InGaP etch-stopper layer, a 150-nm *n*-doped GaAs emitter contact layer (1×10^{19} cm^{-3}), a 10-nm *n*-doped InAlP window layer (5×10^{17} cm^{-3}), InGaP junction layers (40-nm *n*-InGaP (1×10^{18} cm^{-3})/550-nm *p*-InGaP(1×10^{17} cm^{-3})/100-nm *p*-InGaP(1×10^{18} cm^{-3})), a 150-nm *p*-doped GaAs base contact layer (1×10^{19} cm^{-3}) in this sequence. Note that the top cell structures were grown in the reverse order. We also prepared *p*-on-*n* top cell structures in similar manners.

We made (100) *n*-on-*p*, (100) *p*-on-*n*, and (111) *p*-on-*n* bottom cell structures by using the ion implantation of P or B and subsequent annealing (900 °C, 1 min.). The acceleration energy for the ion implantation was 10 keV. The concentration of dopants was nominally 2×10^{20} cm^{-3} at the peak in the as-implanted condition.

In fabricating double junction cells, the base contact layers of the top cell structures were bonded to the bottom cell structures. Next the GaAs wafers were selectively etched off so that the surfaces of the top cell structures were exposed. Three kinds of double junction cells— *n*-on-*p* InGaP/(100) Si, *p*-on-*n* InGaP/(100) Si, and *p*-on-*n* InGaP/(111) Si cells— were made through the conventional device process sequences, i.e., metallization, mesa-etching, and anti-reflection film coating. The cross section of *n*-on-*p* InGaP/(100) Si double junction cells is schematically shown in Fig. 1.

Cell characteristics

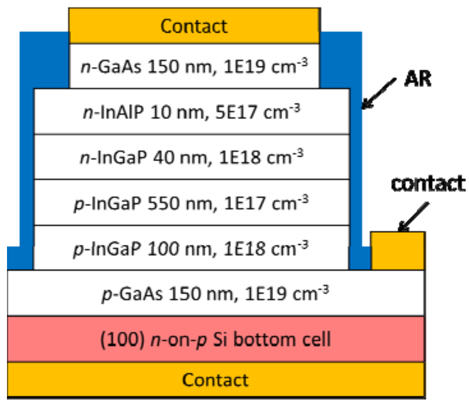

Fig. 1. The schematic cross section of *n*-on-*p* InGaP/(100) Si double junction cells.

We measured the *I-V* characteristics of respective cells under the air mass 1.5G and one-sun condition using an in-house solar simulator. The characteristics of the *n*-on-*p* InGaP/(100) Si double junction cell and the (100) *n*-on-*p* Si bottom cell are shown in Figs. 2(a) and 2(b), respectively. The double junction cell revealed the open circuit voltage (V_{OC}) of 1.85 V, the short circuit current (J_{SC}) of 7.31 mA/cm^2, the fill factor (FF) of 81.9%, and the efficiency of 11.1%, respectively. The top cell, which is a part of the double junction cell, revealed V_{OC} of 1.32 V, J_{SC} of 7.26 mA/cm^2, FF of 65.4%, and the efficiency of 6.3%, respectively. Those of the bottom cell are 0.55 V (V_{OC}), 26.50 mA/cm^2 (J_{SC}), 68.1% (FF), and 9.9% (efficiency), respectively. Results for the *n*-on-*p* InGaP/(100) Si double junction cells as well as the other two double junction cells are summarized in Table I.

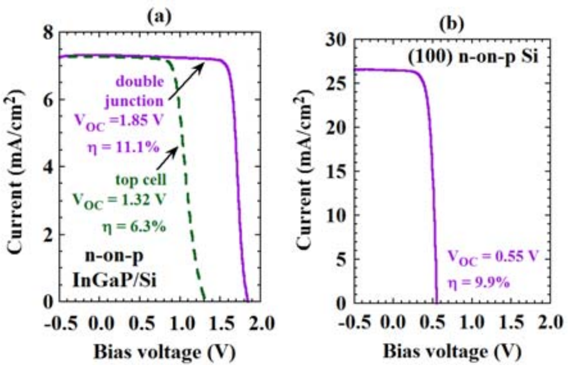

Fig. 2. *I-V* characteristics of (a) *n*-on-*p* InGaP/(100) Si double junction and InGaP top cells and (b) (100) Si bottom cells.

Table I. Characteristics of InGaP/Si double junction cells.

		n-on-*p* InGaP/ (100) Si	*p*-on-*n* InGaP/ (100) Si	*p*-on-*n* InGaP/ (111) Si
Double Junction Cell	V_{OC} (V)	1.85	1.84	1.59
	J_{SC} (mA/cm^2)	7.31	4.08	5.07
	FF (%)	81.9	79.4	77.0
	Efficiency (%)	11.1	6.0	6.2
Top Cell	V_{OC} (V)	1.32	1.30	1.05
	J_{SC} (mA/cm^2)	7.26	3.93	4.72
	FF (%)	65.4	78.0	72.9
	Efficiency (%)	6.3	4.0	3.6
Bottom Cell	V_{OC} (V)	0.55	0.56	0.56
	J_{SC} (mA/cm^2)	26.50	23.66	23.97
	FF (%)	68.1	76.8	77.8
	Efficiency (%)	9.9	10.2	10.4

We find that V_{OC} of each of the double junction cells is almost equal to the sum of the V_{OC} of the top cell and the bottom cell. This means that the top and the bottom cells were electrically connected to each other in accordance with the good conductive properties across the heavily-doped GaAs/Si interfaces [6]. Specifically it is notable that double junction cells composed of (100) InGaP top cells and (111) Si bottom cells were in the normal operation. Furthermore, the efficiency in the *n*-on-*p* InGaP/(100) Si double junction cell is larger than that of either top and bottom cells, which means that the efficiency is enhanced in multi junction cells on Si fabricated by using SAB.

3. Conclusions

InGaP/Si double junction cells were fabricated by using surface activated bonding. The open circuit voltage of double junction cells was almost equal to that of top and bottom cells. The efficiency of *n*-on-*p* InGaP/(100) Si double junction cells was higher than that of either the top and the bottom cells. These results suggest that SAB is applicable for fabricating high efficiency III-V/Si multi junction cells on Si-based bottom cells.

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