InGaP/GaAs/ITO/Si Hybrid Triple-Junction Cells with GaAs/ITO Bonding Interfaces

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***Abstract*—Using surface-activated bonding technologies we fabricate InGaP/GaAs/ITO/Si hybrid triple-junction (3J) cells with p^+-GaAs/ITO and those with n^+-GaAs/ITO bonding interfaces. ITO films deposited on the emitter of Si bottom cells work as intermediate layers between III-V and Si sub cells. The samples are not heated during the bonding process. The photovoltaic characteristics of the fabricated 3J cells are compared with characteristics of conventional 3J cells without intermediate layers. The InGaP/GaAs/ITO/Si 3J cells with n^+-GaAs/ITO bonding interfaces reveal the highest conversion efficiency and the lowest differential resistance among the investigated 3J cells, which implies the potential of ITO-based intermediate layers for achieving more excellent performances of hybrid multi-junction cells.**

I. Introduction

The surface activated bonding (SAB) technologies [1] have successfully been applied for fabricating III-V/Si multi-junction solar cells [2] since dissimilar semiconductor materials with different lattice constants and thermal expansion coefficients can be bonded to each other at low temperatures. It is well understood that the electrical properties of bonding interfaces are influenced by the interface states introduced during the Ar beam irradiation in the SAB process. The performances of hybrid multi-junction cells are, consequently, likely to be limited by the resistance across the bonding interfaces. Although comparatively low interface resistances ($\sim 0.1\ \Omega\mathrm{cm}^2$) were obtained for junctions made of heavily-doped substrates or epitaxially-grown layers [3], the interface resistance in the actual hybrid 3J cells was much higher due to the limited thicknesses (∼several nm) of bonding layers, which also worked as emitters, of Si bottom cells [4].

More importantly, in general, surfaces with the averaged roughness of <1 nm are required so as to achieve firmly-bonded junctions using SAB. This means that the surfaces of bonding layers of the respective sub cells must be flat, i.e., artifacts for enhancing the efficiencies such as textures and passivation films can not be incorporated to the sub cells in fabricating hybrid multi-junction cells.

Here we expect that better performances could be realized in hybrid multi-junction cells by replacing their SAB-based semiconductor/semiconductor junctions by junctions with optically and electrically transparent intermediate layers since such intermediate layers are assumed to play a role of lowering the interface resistance as well as flattening the surfaces of sub cells. In this work, we examine the feasibility of indium-tin-oxide (ITO) films, which are deposited on the emitters of Si bottom cells, as practical candidates for such intermediate layers. All of the investigated junctions and cells are fabricated without heating samples.

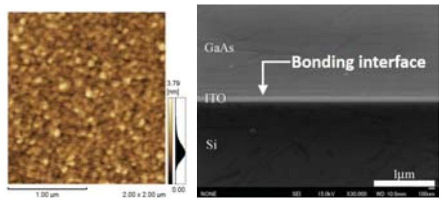

Fig. 1. An AFM image of ITO films deposited on Si substrates as well as a SEM image of GaAs/ITO/Si junctions.

II. Experiments

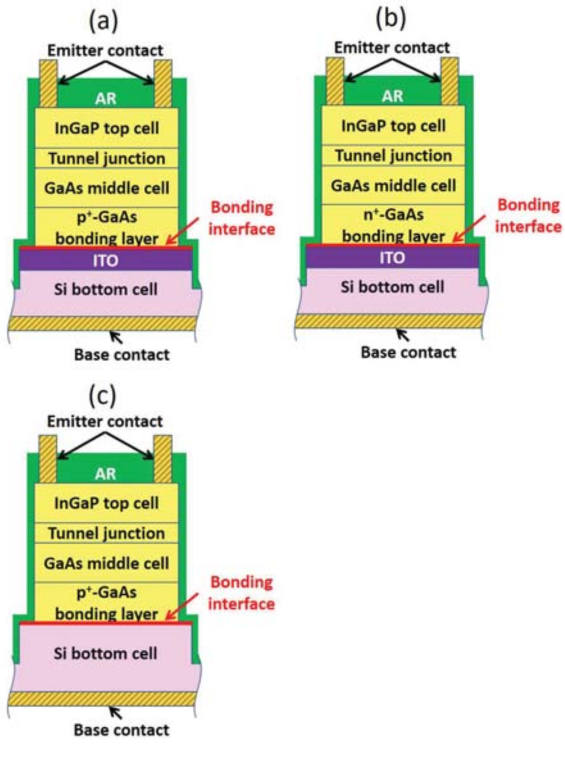

Fig. 2. Schematic cross sections of (a) InGaP/GaAs/ITO/Si 3J cells with p^+-GaAs/ITO bonding interfaces (3J(a)), (b) InGaP/GaAs/ITO/Si 3J cells with n^+-GaAs/ITO bonding interfaces (3J(b)), and (c) InGaP/GaAs/Si 3J cells with p^+-GaAs/n^+-Si bonding interfaces (3J(c)).

In a preparatory study, we performed AFM observations of surfaces of ITO films deposited on Si substrates. We found that the averaged roughness in surfaces of ITO films was $\approx$ 0.3 nm as is shown in Fig. 1, which was small enough for the films to be firmly bonded. We actually confirmed that ITO films deposited on Si substrates were bonded to other Si substrates and the obtained Si/ITO/Si junctions revealed excellent electrical characteristics [5]. In Fig. 1 is also shown an SEM image of GaAs/ITO/Si junctions, which demonstrated that interfaces with no voids were achieved. Furthermore we observed that the transmittance of ITO films was not deteriorated by irradiating Ar beams in the SAB process.

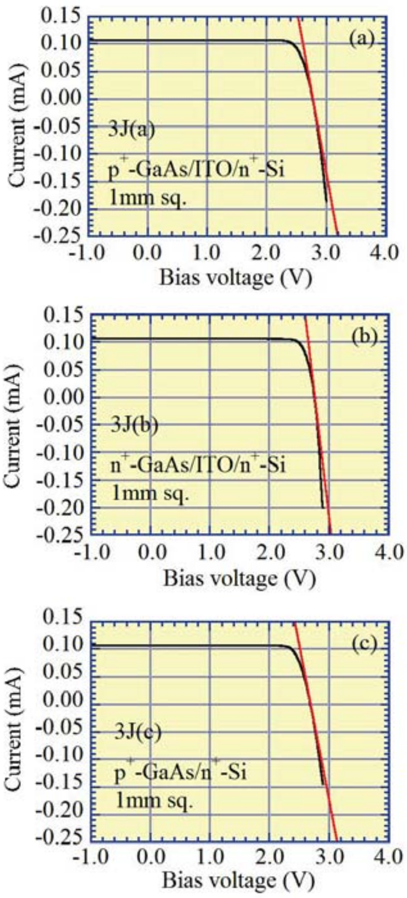

Fig. 3. $I-V$ characteristics of (a) 3J(a), (b) 3J(b), and (c) 3J(c) cells.

TABLE I
CHARACTERISTIC PARAMETERS OF THE HYBRID 3J CELLS.

3J type	3J(a)	3J(b)	3J(c)
short-circuit current (mA)	0.106	0.107	0.106
open-circuit voltage (V)	2.77	2.76	2.67
FF (%)	83.4	85.6	84.1
-dV/dI @0 mA (Ω)	1700	1130	1800
as-measured efficiency (%)	24.6	25.1	24.0

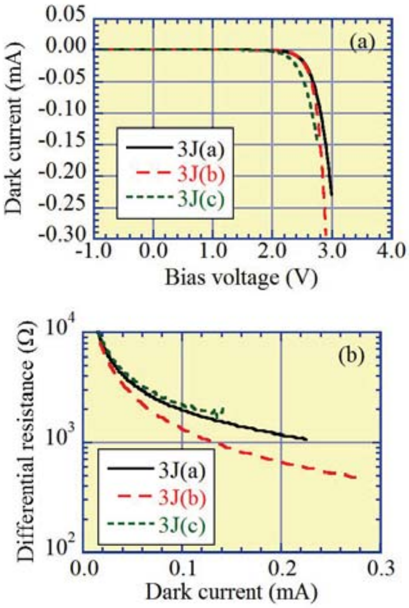

Fig. 4. (a) $I-V$ characteristics of the 3J cells in the dark. (b) The relationships between the differential resistance and the dark current of the 3J cells in the dark.

90-nm-thick ITO films were deposited on the several-nm-thick n^+-Si emitters of Si bottom cells. The emitters were fabricated by the ion implantation and annealing. We prepared n-on-p InGaP/GaAs 2J heterostructures with p^+-GaAs bonding layers and those with n^+-GaAs bonding layers. We bonded each of the 2J heterostructures to the Si bottom cells with the capping ITO films. By using previously-reported process steps [2], we fabricated two types of InGaP/GaAs/ITO/Si hybrid 3J cells, or 3J(a) and 3J(b), which are equipped with p^+-GaAs/ITO and n^+-GaAs/ITO bonding interfaces, respectively. In addition we prepared 3J cells with p^+-GaAs/n^+-Si bonding interfaces (3J(c)). The schematic cross sections of the 3J(a), 3J(b), and 3J(c) cells are shown in Figs. 2(a), 2(b), and 2(c), respectively. The mesa area of the respective 3J cells was 1 mm^2.

The current-voltage (I-V) characteristics of the 3J cells under the air mass 1.5G/one sun irradiance, which were measured using in-house facilities, are shown in Figs. 3(a), 3(b), and 3(c) for 3J(a), 3J(b), and 3J(c), respectively. Values of parameters characterizing the respective curves are summarized in Table I. The conversion efficiencies of the respective cells were 24.6 (3J(a)), 25.1 (3J(b)), and 24.0% (3J(c)). Their differential resistance at I = 0 mA, which we obtained by the least-square fitting, was 1700, 1130, and 1800 Ω for 3J(a), 3J(b), and 3J(c), respectively, as is seen from the slopes of the red straight lines in the figures. The intrinsic conversion efficiency of the 3J(b) cell was estimated to be $\approx$ 27% by compensating the shadow loss of the emitter contacts and the estimated contribution of the 10-μm Si periphery.

The I-V characteristics of the 3J cells measured in the dark are shown in Fig. 4(a). The relationships between the differen-

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tial resistance and the dark current, which were obtained from the respective I-V curves, are shown in Fig. 4(b). We find that the differential resistance was lowered by employing the ITO intermediate layers. The lowest resistance was obtained in 3J(b), or 3J cells with n^+-GaAs/ITO bonding interfaces.

The difference in resistance in the dark among the three 3J cells is consistent with the results under the solar irradiance. The difference between 3J(a) and 3J(b) is explained by the n-type features of ITO films. The obtained results indicate that the ITO intermediate layers should play a role of lowering the series resistance in hybrid multijunciton cells and are useful in achieving higher efficiencies in hybrid multi-junction cells.

III. Conclusion

We successfully fabricated InGaP/GaAs/ITO/Si hybrid 3J cells using the SAB technologies. The 3J cells with n^+-GaAs/ITO bonding interfaces revealed higher conversion efficiencies and lower interface resistances in comparison with the 3J cells with p^+-GaAs/ITO or p^+-GaAs/n^+-Si bonding interfaces. The results imply that the ITO films should be applicable as intermediate layers in hybrid multi-junction cells.

Acknowledgment

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