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2012 Jpn. J. Appl. Phys. 51 080208

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InGaP/GaAs Dual-Junction Solar Cell with AlGaAs/GaAs Tunnel Diode Grown on 10° off Misoriented GaAs Substrate

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Received March 26, 2012; accepted May 25, 2012; published online July 23, 2012

InGaP/GaAs dual-junction solar cells with different tunnel diodes (TDs) grown on misoriented GaAs substrates are investigated. It is demonstrated that the solar cells with P⁺⁺-AlGaAs/N⁺⁺-GaAs TDs grown on 10° off GaAs substrates not only show a higher external quantum efficiency (EQE) but also generate a higher peak current density (J_{peak}) at higher concentration ratios (185x) than the solar cells with P⁺⁺-GaAs/N⁺⁺-InGaP TDs grown on 6° off GaAs substrates. Furthermore, the cell design with P⁺⁺-AlGaAs/N⁺⁺-GaAs TDs grown on 10° off GaAs substrates does not generate a disordered InGaP epitaxial layer during material growth, and thus shows superior current–voltage characteristics.

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A tunnel diode (TD), which must be both highly transparent and heavily doped, acts as a series connection between tandem solar cells. It is a very important component in III–V multijunction solar cells, as III–V solar cell devices have to be operated at higher concentration ratios. If, at higher concentrations, the peak current density (J_{peak}) in the TD is lower than the short-circuit current density (J_{sc}), the overall performance of III–V tandem solar cells will be markedly affected. Currently, for III–V multijunction solar cells, wide band gap materials with a low electrical resistivity, such as AlGaAs and InGaP, are adopted as TD materials because of their lower optical absorption. In fact, the increase in the band gap of TD materials made from III–V semiconductors results in a decrease in tunneling current density. This implies that the reduction in impurities in TDs, such as oxygen atoms that act as nonradiative traps, is very important when higher band gap materials are used.

The AlGaAs epitaxial layer is a very important material for many high-speed electronic and optoelectronic devices,^{1,2)} because the difference in the lattice parameters between GaAs and AlGaAs is very small, which prevents the generation of undesirable interface states. However, the AlGaAs epitaxial layer as a TD material is known to have a serious oxygen incorporation problem as compared with InGaP epitaxial layer for III–V multijunction solar cell application. InGaP TDs show a lower interface recombination rate than AlGaAs TDs when electrons move away from the TD interface. In a previous work, we proved that the 10° off misorientation GaAs substrates not only reduce the oxygen-impurity content in the N⁺⁺-GaAs/P⁺⁺-AlGaAs TD, but also produce high-quality TD with a smooth surface and a sharp interface.³⁾ Although the 10° off misoriented GaAs substrate can efficiently reduce nonradiative traps in the N⁺⁺-GaAs/P⁺⁺-AlGaAs TD, a dual-junction solar cell grown on 10° off misorientation GaAs substrates using a N⁺⁺-GaAs/P⁺⁺-AlGaAs TD has not yet been reported.

In this paper, we report the results of comparison between InGaP/GaAs dual-junction solar cells with a N⁺⁺-InGaP/P⁺⁺-GaAs TD (sample A) and those with a N⁺⁺-GaAs/P⁺⁺-AlGaAs TD (sample B), both grown on 10° off misorienta-

tion GaAs substrates, and also of a N⁺⁺-InGaP/P⁺⁺-GaAs TD grown on 6° off misorientation GaAs substrates (sample C) using a metal organic chemical vapor deposition (MOCVD; EMCORE D180) system. Trimethylgallium (TMG), trimethylaluminum (TMAI), and trimethylindium (TMIn) were used as group III sources, whereas arsine (AsH₃) and phosphine (PH₃) were used as group V sources. The precursors for p- and n-type dopants were carbon-tetrabromide (CBr₄) and dimethyl-telluride (DMTe), respectively. For GaAs/AlGaAs TDs, higher doping levels can be accomplished in AlGaAs epilayers with carbon doping than in GaAs. The GaAs epitaxial layer used for the n-type side in the TDs was found to have lower optical absorption because of the generation of the Burstein–Moss shift.⁴⁾ The band gap of n-type GaAs in the TDs slightly increases with the increase in doping concentration, resulting in more light passing through the TD to the GaAs cell. For an InGaP/GaAs TD, carbon-doped InGaP was not used in this study because carbon is very difficult to embed in InP-based materials by MOCVD. All films in this study were grown at a low pressure of 40 Torr and a hydrogen flow rate of 28000 sccm.

Figures 1(a) and 1(b) show the layer structures of the InGaP/GaAs dual-junction solar cells with different TD materials. The framed GaAs bottom cell consists of a 0.1 μm InGaP back surface field (BSF) layer, a 3 μm GaAs base layer, a 0.1 μm GaAs emitter layer, and a 0.05 μm InGaP window layer. The InGaP top cell consists of a 0.03 μm AlInP BSF layer, a 0.5 μm InGaP base layer, a 0.05 μm InGaP emitter layer, and a 0.03 μm AlInP window layer. A multi-layer metal consists of Ni (6 nm)/Ge (50 nm)/Au (100 nm)/Ni (45 nm)/Au (250 nm) was used as the front contact, and a Ti (50 nm)/Pt (60 nm)/Au (250 nm) layer was used as the back contact in this study. The antireflection coating is a single layer of Si₃N₄ with a thickness of 75 nm.

Figure 2 shows the current–voltage (I – V) characteristics of the InGaP/GaAs dual-junction solar cells with P⁺⁺-GaAs/N⁺⁺-InGaP (sample A), and P⁺⁺-AlGaAs/N⁺⁺-GaAs TDs (sample B) grown on the 10° off GaAs substrate and with P⁺⁺-GaAs/N⁺⁺-InGaP TD grown on the 6° off GaAs substrate (sample C), respectively. The 6° off GaAs substrates were often used as substrates for III–V solar cell applications,^{5–7)} which makes it easy to transfer the growth

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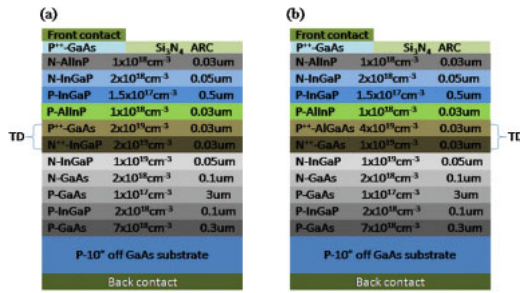


Fig. 1. (Color online) Structures of InGaP/GaAs dual-junction solar cells with different tunnel diode materials: (a) the cell design with P⁺⁺-GaAs/N⁺⁺-InGaP tunnel diode (TD), (b) the cell design with P⁺⁺-AlGaAs/N⁺⁺-GaAs TD.

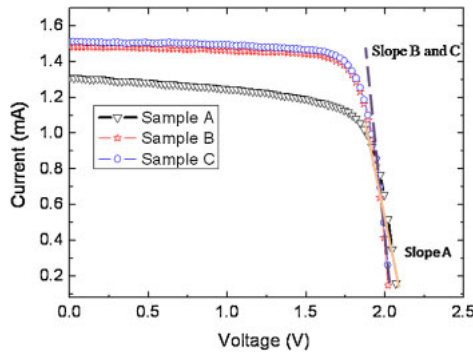


Fig. 2. (Color online) *I*–*V* characteristics of InGaP/GaAs dual-junction solar cells measured at one sun. Sample A: the cell design with a P⁺⁺-GaAs/N⁺⁺-InGaP TD grown on 10° off misorientation GaAs substrates; sample B: the cell design with a P⁺⁺-AlGaAs/N⁺⁺-GaAs TD grown on 10° off misorientation GaAs substrates; sample C: the cell design with a P⁺⁺-GaAs/N⁺⁺-InGaP TD grown on 6° off misorientation GaAs substrates.

parameters to Ge substrates. Therefore, it is suitable as a standard reference for the dual-junction solar cell grown on misoriented GaAs substrates in this study. Table I shows the performance comparison of samples A, B, and C measured at one sun, including open-circuit voltage (*V*_{oc}), short-circuit current density (*J*_{sc}), fill factor (FF), and conversion efficiency (Eff). From the experimental results, *J*_{sc} of sample A is smaller than those of samples B and C. *J*_{sc} generated by a III–V multijunction solar cell is dependent on the incident light and can be simulated using the following equation:⁸⁾

$$J_{sc} = \int_0^{\infty} \eta_c(E)[1 - R(E)]a(E)b_s(E) dE, \quad (1)$$

where $\eta_c(E)$ is the probability of electrons collected under illumination; $R(E)$ is the probability of photon reflection; $a(E)$ is the probability of absorption of a photon of energy E ; and $b_s(E)$ is the incident spectral photon flux density. Equation (1) shows that a low quantum efficiency (QE) may lead to a reduction in J_{sc} for a solar cell device operated under illumination. QE depends on the cell design and epitaxial quality. For all samples reported in this study, the cell design and growth parameters for each subcell of the InGaP/GaAs dual-junction solar cells are the same. The external quantum efficiency (EQE) of sample A is lower than those of samples B and C, as shown in Fig. 3, implying that the epitaxial quality of sample A is inferior.

Table I. *I*–*V* characteristics of the InGaP/GaAs dual-junction solar cells with different tunnel diodes grown on misoriented GaAs substrates.

Tunnel junction	<i>V</i> _{oc} (V)	<i>I</i> _{sc} (mA/cm ²)	FF (%)	Eff (%)
Sample A	2.07	10.5	72.0	15.78
Sample B	2.03	11.9	78.9	19.24
Sample C	2.04	12.1	79.2	19.55

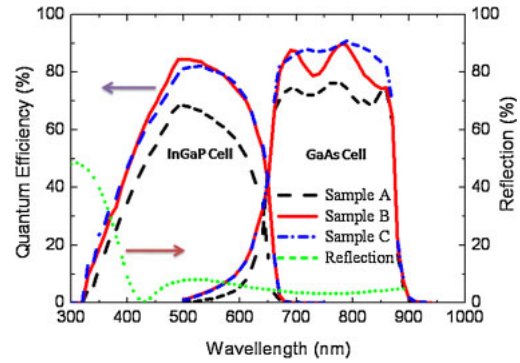


Fig. 3. (Color online) PL of InGaP/GaAs dual-junction solar cells. Sample A: the cell design with a P⁺⁺-GaAs/N⁺⁺-InGaP TD grown on 10° off misorientation GaAs substrates; sample B: the cell design with a P⁺⁺-AlGaAs/N⁺⁺-GaAs TD grown on 10° off misorientation GaAs substrates; sample C: the cell design with a P⁺⁺-GaAs/N⁺⁺-InGaP TD grown on 6° off misorientation GaAs substrates.

The characteristics of the dual-junction solar cells with different TD materials, such as P⁺⁺-GaAs/N⁺⁺-InGaP and P⁺⁺-AlGaAs/N⁺⁺-GaAs, grown on 10° off GaAs substrates are investigated on the basis of the spectral responses of the EQE of the dual-junction solar cells, as shown in Fig. 3. The spectral response of the dual junction solar cell with the P⁺⁺-GaAs/N⁺⁺-InGaP TD grown on the 6° off GaAs substrate is also shown in Fig. 3. The non-square shape of the spectral responses of the InGaP top cell is observed owing to higher reflection losses (10–50%) in the range from 300 to 500 nm. From the experimental results, it is found that the total EQE of the dual-junction solar cells with the P⁺⁺-AlGaAs/N⁺⁺-GaAs TD (sample B) is higher than that with the P⁺⁺-GaAs/N⁺⁺-InGaP TD (sample A) at the same misorientation angle (10° off). The maximum EQEs of sample B are 82% for the InGaP top cell and 85% for the GaAs bottom cell. An increase in the EQE of the GaAs bottom cell of sample B is confirmed, and this is due to the smaller absorption losses in the P⁺⁺-AlGaAs/N⁺⁺-GaAs TD than in sample A. On the other hand, the total EQE of sample B is almost the same as that of the traditional dual junction with a P⁺⁺-GaAs/N⁺⁺-InGaP TD grown on the 6° off GaAs substrate (sample C), suggesting that 10° off misorientation GaAs substrates not only reduce contamination³⁾ in N⁺⁺-GaAs/P⁺⁺-AlGaAs TDs but also produce a high EQE when solar light is injected into the solar cell.

In order to determine the reason for the inferior epitaxial quality of sample A, photoluminescence (PL) using a 532 nm laser source was employed to determine the band gap and epitaxial quality. It is found that the band gap of the InGaP cell of sample A is 1.92 eV, which is larger than those of samples B and C (1.82 and 1.85 eV, respectively). It is suggested that a transition of an ordering/disordering InGaP epitaxial layer may occur in sample A when the higher substrate misorienta-

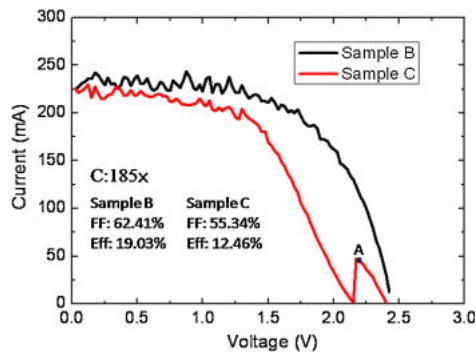


Fig. 4. (Color online) I - V characteristics of InGaP/GaAs dual-junction solar cells operated at higher concentration ratios ($185\times$). Sample A: the cell design with a P^{++} -GaAs/ N^{++} -InGaP TD grown on 10° off misorientation GaAs substrates; sample B: the cell design with a P^{++} -AlGaAs/ N^{++} -GaAs TD grown on 10° off misorientation GaAs substrates; sample C: the cell design with a P^{++} -GaAs/ N^{++} -InGaP TD grown on 6° off misorientation GaAs substrates.

tion angle (10° off) was adopted.^{9,10} The poor epitaxial quality of sample A is attributed to crystal defects associated with disordered structures in the matrix, which further decreases QE and J_{sc} of III-V solar cells devices. Experiments also confirmed that InGaP/GaAs dual-junction solar cells with a P^{++} -AlGaAs/ N^{++} -GaAs TD grown on 10° off GaAs substrate (sample B) do not generate a disordering InGaP epitaxial layer during material growth, and thus results in superior I - V characteristics. Besides, the slope of sample A is lower than those of samples B and C, as shown in Fig. 2, suggesting that the series resistance (R_s) of sample A is higher than those of the others. Higher series resistance also leads to lower FF and J_{sc} of III-V solar cells devices.

To further understand the difference in the I - V characteristics at higher concentration ratios, samples B and C were operated under average solar concentrations of approximately $185\times$ and the results are shown in Fig. 4. Experimental results confirmed that the FFs and conversion efficiencies of samples B and C both decrease at higher concentration ratios because of larger R_s . The thickness of the front contact used in this study was too thin (~ 450 nm), which results in larger R_s when solar cell devices were operated at higher concentration ratios. Only one operating point A in Fig. 4 is found in the I - V curve of sample C, implying that the R_s value is lower than the negative differential resistivity^{11,12} even if the thickness of the front contact is not sufficient. For III-V multijunction solar cells, a lower R_s value relative to the negative differential resistivity of the tunnel diode is necessary. On the other hand, a sharp current drop occurs at a lower voltage of 2.1 V for sample C, and no dip in the I - V characteristic exists in sample B. These results indicate that, at higher concentration ratios ($185\times$), the P^{++} -AlGaAs/ N^{++} -GaAs TD grown on the 10° off GaAs substrate generates a higher peak current density (J_{peak}) than the P^{++} -GaAs/ N^{++} -InGaP TD grown on the 6° off GaAs substrate.

When the tunneling current density of a TD (J_{peak}) in III-V multijunction solar cell is lower than the short-circuit current density of the cell (J_{sc}) at higher concentration ratios, the probability of an electron tunneling from the occupied states to the unoccupied states on the hole side decreases, and a current drop occurs at a lower voltage. The AlGaAs/GaAs hetero-

structure possesses a larger energy-band difference in the conduction band than the GaAs/InGaP heterostructure,^{13,14} which can effectively increase the tunneling current of a TD by reducing the tunneling barrier and tunneling width when III-V solar cell devices are operated at higher concentration ratios.

In summary, we have demonstrated that, compared with the cell design with a P^{++} -GaAs/ N^{++} -InGaP TD (sample A), InGaP/GaAs dual junction solar cells with a P^{++} -AlGaAs/ N^{++} -GaAs TD grown on 10° off GaAs substrates (sample B) exhibit superior photovoltaic conversion efficiency when operated at one sun. The cell design with a P^{++} -GaAs/ N^{++} -InGaP TD grown on the 10° off GaAs substrate generates a disordering InGaP epitaxial layer during material growth. This implies that the higher substrate misorientation angle, such as 10° off, may result in a disordering InGaP epitaxial layer.^{9,10} However, the disordering InGaP structure did not appear in sample B. It is believed that the cell design with a P^{++} -AlGaAs/ N^{++} -GaAs TD grown on the 10° off GaAs substrate can suppress the generation of the disordering InGaP structure during material growth. Besides, higher R_s for sample A also lead to the degradation of FF and J_{sc} of III-V solar cells, as shown in Fig. 2. Moreover, the InGaP/GaAs dual-junction solar cell with a P^{++} -AlGaAs/ N^{++} -GaAs TD grown on 10° off misorientation GaAs substrates produces higher EQE ($\sim 82\%$ for InGaP top cell and 85% for GaAs bottom cell) than the InGaP/GaAs dual-junction solar cell with a P^{++} -GaAs/ N^{++} -InGaP TD, as shown in Fig. 3. Furthermore, when these solar cells were operated at higher concentration ratios, sample B exhibited superior I - V characteristics owing to a larger energy-band difference in the conduction band of AlGaAs/GaAs TD, as shown in Fig. 4. These results suggest that InGaP/GaAs dual-junction solar cells with a P^{++} -AlGaAs/ N^{++} -GaAs TD grown on 10° off misorientation GaAs substrates not only produce a high EQE but also generate a higher peak current density (J_{peak}) at higher concentration ratios ($185\times$) than that with a P^{++} -GaAs/ N^{++} -InGaP TD grown on the 6° off GaAs substrate.

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