The Effects of Growth Temperature and Substrate Tilt Angle on GaInP/GaAs Tandem Solar Cells

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***Abstract*—The performance of GaInP/GaAs tandem solar cells with AlInP growth temperatures of 680 ℃ and 700 ℃ on n-type GaAs (100) substrate with 2° and 6° tilt angles has been investigated. The series resistance and open circuit voltage of the fabricated tandem solar cells are affected by the substrate tilt angles and the growth temperatures of the window layer when zinc is doped in the tunnel diode. With carbon doping as a p-type doping source in the tunnel diode and the effort of current matching between top and bottom cells, GaInP/GaAs tandem solar cell has been exhibited 25.58% efficiency.**

***Index Terms*—Solar cell, tandem solar cell, GaAs compound semiconductor**

I. Introduction

Recently, the high efficiency multijunction concentrator cells have been exhibited the potential to revolutionize the cost-effective system of photovoltaic electricity generation. [1-3]. Multi-junction concentrator cells consist of a concentrator and a small area and high efficiency compound semiconductor cell compared with conventional silicon cells. The extremely small cell area with highly concentrated sun light and high efficiency capability of the multi-junction concentration cells can be effective to solve material shortage of photovoltaic cells.

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III-V compound semiconductors, especially GaAs, have been extensively utilized to optoelectronic devices including photovoltaic electricity generation. GaAs has good inherent properties such as good radiation-resistance, low temperature coefficient, and high conversion efficiency potential [4]. For the two junction tandem solar cell, p-type doped GaAs substrates have been generally utilized in order to minimize the top contact series resistance of a solar cell. However, p-type GaAs substrates have high etch pit density (5000 cm^{-3}) compared with those (500 cm^{-3}) of n-type substrates, where etch pit density presents the substrate quality as a crystal. Since high quality epi-structure can provide high carrier mobilities and low recombination velocities in surface and bulk regions, low etch pit density substrates are preferable for high efficiency solar cells. The doping concentration of the epi-layer can be affected by the substrate tilt angle [5] and the growth temperature of the specific layer, especially AlInP window layer, may also affect the solar cell efficiency. However, there is no research on the effect of the substrate tilt angle and the growth temperature on the solar cell efficiency. Therefore, researches on the effects of n-type substrate tilt angles and growth temperatures on the GaInP/GaAs tandem solar cell performance are required.

GaInP/GaAs tandem solar cells using n-type GaAs substrate with different substrate tilt angles and growth temperatures of the AlInP window layer were investigated.

II. Design, Fabrication and Optimization

An AIXTRON multiwafer metal-organic chemical vapor deposition reactor (AIX2600 G3 IC) was used to grow the solar cell epi-structures. AsH_3, PH_3, TMGa, TMIn, and TMAl were used as precursors. SiH_4 and DMZn were employed as doping sources. Epi-structures were grown on n-type GaAs (100) substrates with 2° or 6° off-orientation toward (111). The growth conditions were pressure=50 mbar, and temperature=680-700 ℃.

A single junction solar cell and four different double junction solar cells have been fabricated, which are described as follows:

1) single junction cell structure (Fig. 1 (a))

2) two junction cell with 2° and 6° tilted substrates with 680 ℃ and 700 ℃ AlInP growth temperatures (Fig. 1 (b)).

GaAs single junction solar cell is generally used as a bottom cell of a GaInP/GaAs tandem solar cell. Thus, the performance of the GaAs single junction solar cell should be verified before design and fabrication of a tandem solar cell in order to achieve high efficiency. The fabricated single junction cell consists of 0.2 μm-thick GaAs buffer, 0.05 μm-thick GaInP back surface field (BSF), 3.5 μm-thick GaAs base, 0.5 μm-thick GaAs emitter, 0.03 μm-thick AlInP window, and 0.03 μm-thick GaAs cap layers, where the BSF and window layers were used as potential barriers. Conventional GaAs process techniques such as ohmic metalization, mesa isolation, anti-reflection coating, scribing, and breaking were used. For ohmic contact formations, a Ti/Pt/Au p-front side contact with a resistivity of r_c <10 μΩ · cm^2 was applied with rapid thermal annealing. The whole backside was covered with a AuGe/Ni/Au n-backside contact (r_c < 1 μΩ · cm^2). Conventional wet chemical were performed for mesa etching. Fabricated solar cells were mounted on printed circuit boards and Au-wire bonding performed. Fig. 2 shows a photograph of an assembled solar cell with total cell area of 1 cm^2 on a printed circuit board.

In order to minimize the reflection, double layer anti-reflection coating were designed using Macleod and deposited on the device surfaces with thickness of 600 nm-SiO_2 and 500 nm-SiN, respectively. The reflectance between the air and the cell with anti-reflection coating was measured using a UV-Vis and the result is shown in Fig. 3 with the external quantum efficiency. The minimum of the reflection is at 650 nm where the number of photons is maximum for air-mass 1.5 global standards. The developed anti-reflection coating can provide approximately 30.3 mA/cm^2-short circuit current density (J_{sc}) if the internal quantum efficiency of the cell is unity. Since the best short circuit current density of a GaAs single junction cell is 28.86 mA/cm^2 [6], the calculated J_{sc} of 30.3 mA/cm^2 can be affordable to attain high efficiency cell. The external quantum efficiency shown in the Fig. 3 corresponds with the reflection curve for the wavelength range from 600 nm to 900 nm. The measured current voltage characteristics (under one-sun air-mass 1.5 global illumination with the cell area of 1.0 cm^2) exhibited 23.94% efficiency as shown in Fig. 3 where a class A solar simulator (Wacom : WXS-220S-L2) was used. The short circuit current density and fill factor are

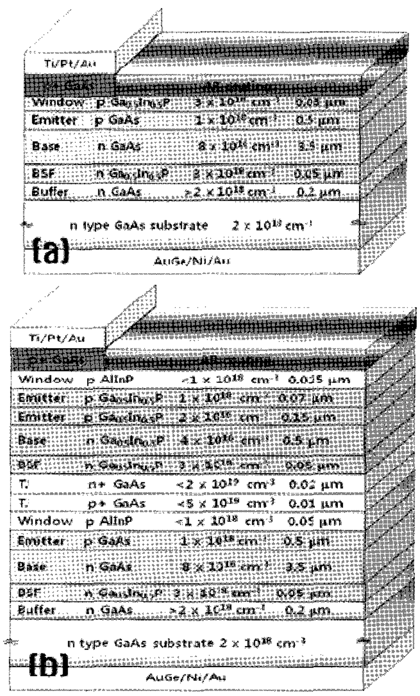


Fig. 1. Schematic of cross sections of the (a) GaAs single and (b) GaInP/GaAs tandem solar cells, respectively.

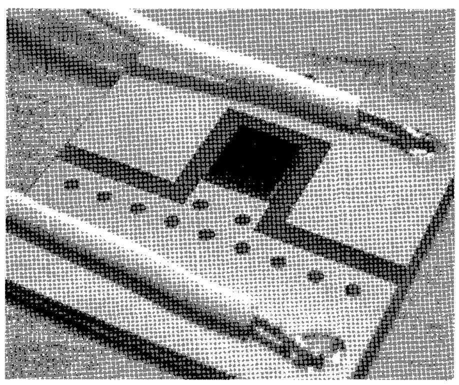


Fig. 2. Photograph of an assembled solar cell for measurement.

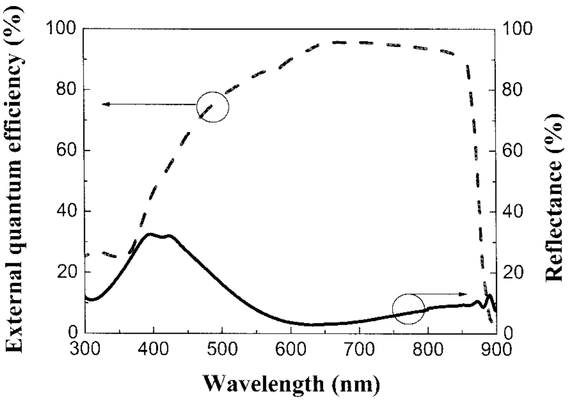
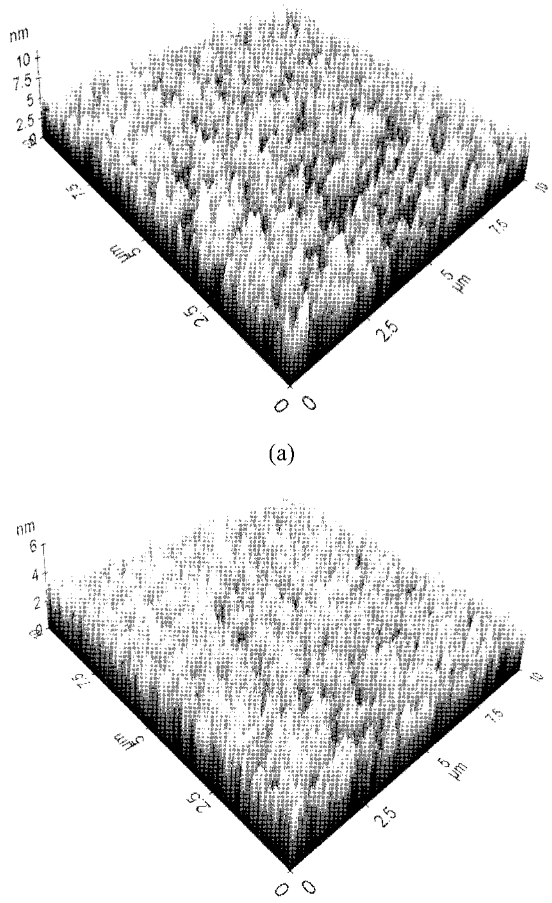


Fig. 3. Measured reflectance and external quantum efficiency of the fabricated GaAs single junction cell.

27.05 mA/cm^2 and 84.5%, respectively. The short circuit current density implies that the anti-reflection coating works well and the carrier recombination in the cell is sufficiently low for fabrication of high efficiency GaInP/GaAs tandem cell. High fill factor of 84.5% stems from the low series resistance of 1.9 Ω thanks to the good ohmic contact formation and low resistance wire bonding.

The GaInP/GaAs tandem solar cell requires a tunnel diode between GaInP top and GaAs bottom cells. The tunnel diode should have high doping concentration to have low series resistance for high performance tandem solar cells [7]. Generally, high growth temperature condition accelerates the diffusion of dopant in a semiconductor, whereas the potential of good epi-structure morphology increases. Besides, the substrate tilt angle can also affect the dopant diffusion and morphology of the epi-structure surface. Fig. 4 shows the AFM images of 0.5 μm-thick AlInP layer grown on 2° and 6° off-orientation toward (111) at 700 ℃. To investigate the effect of the substrate tilt angle and growth temperature of AlInP window layer on the performance of GaInP/GaAs tandem solar cells, four different cell conditions shown in Table 1 were fabricated.

The measured current voltage characteristics of four tandem cells under one-sun air-mass 1.5 global illumination with the cell area of 1.0 cm^2 are shown in Fig. 5 and the performances are summarized in Table 1. The best cell efficiency of 24.10% was obtained from 2° substrate tilt angle and 680 ℃ AlInP window layer growth temperature. The series resistances of cell A and B having 2 ° and 6 ° substrate tilt angles at 680 ℃ in Table 1, are 16.9 and 36.2 Ω, respectively. The cell B with 6°



(a)

(b)

Fig. 4. AFM images of the 0.5 μm-thick AlInP layer surface morphology grown on (a) 2° and (b) 6° tilted substrates at 700 ℃.

Table 1. The conditions of substrate tilt angle and growth temperatures of AlInP window layer of the fabricated GaInP/GaAs tandem solar cells and measured performance summary

Cells	A	B	C	D
AlInP growth temperature	680 ℃		700 ℃	
Substrate tilt angle	2°	6°	2°	6°
Efficiency (%)	24.10	16.1	14.9	15.7
J_{sc} (mA/cm^2)	12.9	13.0	12. 9	13.2
V_{oc} (V)	2.37	1.81	1.87	1.88
F.F. (%)	79	68	61	63
Series resistance (Ω)	16.9	36.2	41.4	46.9
rms roughness (Å)	11.3	-	9.5	5.8

substrate tilt angle shows much higher series resistance compared with the cell A due to the high zinc diffusion velocity [7]. Therefore, it is believed that the substrate tilt angle can affect the tunnel junction characteristics,

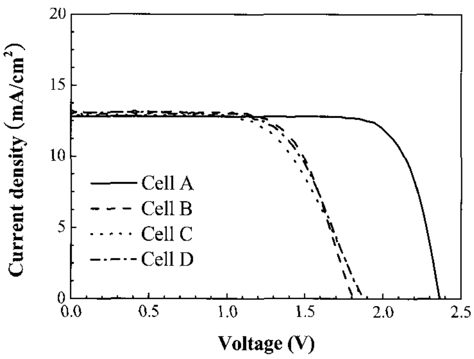


Fig. 5. Illuminated current voltage curves of the fabricated GaInP/GaAs tandem solar cells under one-sun air-mass 1.5 global illumination with the cell area of 1.0 cm^2.

especially the series resistance, since the resistance components such as p(n)-ohmic contacts, window, emitter, and base resistances could not be larger than 10 $\Omega \cdot cm^2$.

The cell D with 6° substrate tilt angle shows 5.8 Ω higher resistance than that of cell C with 2°. This result is consistent with the cell A and B grown at 680 ℃. Thus, substrate tilt angle can affect the series resistance of the cells regardless of the AlInP growth temperature.

The cell C and D with AlInP grown at 700 ℃ show over 40 Ω series resistances. These high resistance results imply that the increased growth temperature of AlInP-window layer can increase the series resistance of cell. To investigate the origin of the AlInP growth temperature, hole concentration of 0.5 μm-thick AlInP layer grown on 2° tilted GaAs substrate as a function of growth temperature was measured, where an electrochemical capacitance-voltage profiler was utilized. The hole concentration measurement result is shown in Fig. 6. It decreases as the AlInP growth temperature increases. The low hole concentration of AlInP layer grown at 700 ℃ compared

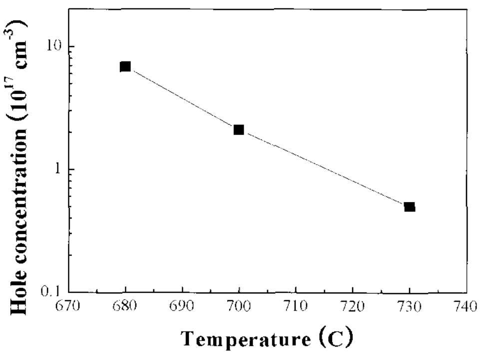


Fig. 6. The hole concentration of 0.5 μm-thick-AlInP layer grown on 2° tilted GaAs substrate as a function of growth temperature.

with that of grown at 680 ℃ can accelerate the diffusion of the zinc in the p-type tunnel diode due to the large gradient of dopant concentration between AlInP and GaAs, decreasing p-type doping concentration of the tunnel diode. This should be avoided to minimize the tunnel diode resistance, since the low doping concentration of a tunnel diode increases its resistance near zero bias. The low growth temperature of the AlInP window layer is preferable to form low resistance of a tunnel diode due to relatively high hole concentration in AlInP layer, based on the experimental results.

The open circuit voltages (V_{oc}) of cell B, C, and D in the Fig. 5 are about 1.9 V. while the cell A shows 2.37 V. Although rigorous studies about these differences have to be performed, it is believed that the voltage drop through the series resistance of tunnel junction (>40 Ω) in the middle of the tandem cell might cause voltage drop of 0.5 V. Therefore, GaInP/GaAs tandem solar cell should employ a low resistance tunnel diode for high efficiency. Low diffusivity doping source such as carbon is required for low resistance tunnel diode.

Fig. 7 shows the external quantum efficiency top and bottom cell for cell A. It was measured using a quantum efficiency measurement system (QEX7) under illumination of properly selected bias light to saturate current of each sub cell. The short circuit current density of top and bottom cell can be calculated using the equation;

$$J_{sc} = \int_0^{\infty} QE(\lambda) b_s(\lambda) d\lambda, \qquad (1)$$

where q, QE(λ), $b_s(\lambda)$, and λ are elementary charge, external quantum efficiency, spectral photon flux, and wavelength, respectively. For the wavelength ranges from 300 to 900 nm, the current generated in the top and bottom cells are 14.6 mA/cm^2 and 12.4 mA/cm^2, respectively. This implies that the GaInP top cell is so thick to absorb larger amount of photons than that of the GaAs bottom cell. Since the amount of current mismatch is 1.8 mA/cm^2 (14.2%), this mismatch current can induce 1.8% efficiency loss assuming the peak power voltage of 2.0 V. This mismatch current induced loss should be eliminated by optimizing the thickness of GaInP top cell.

The optimization of the GaInP top cell thickness to eliminate the current loss due to their mismatch with carbon doping as p-type dopant in the tunnel diode was performed. A GaInP top cell with 0.63 μm-thick, reduction of 0.14 μm GaInP thickness, was used. Fig. 8 (a) shows the quantum efficiency of the modified cell. The top cell quantum efficiency of the modified cell is reduced, while that of the bottom cell is increased. As a result the calculated current densities are approximately matched within 0.2%. Fig. 8 (b) shows the current voltage characteristic under the under air-mass 1.5 global illumination with the cell area of 1 cm^2 and the efficiency is 25.58%. The series resistance reduced and the open circuit voltage increased.

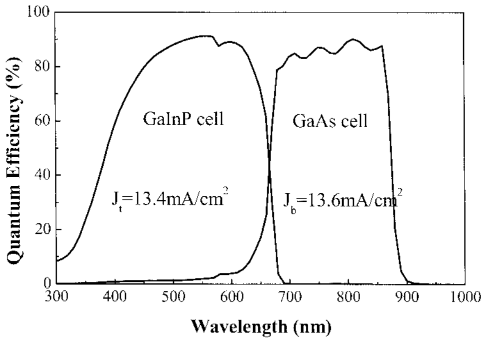


Fig. 7. External quantum efficiency characteristics of the GaInP and GaAs sub cells grown on 2° tilt substrate, of which AlInP window layer growth temperature is 680 ℃, shows current mismatch of 1.8 mA/cm^2 between the sub cells.

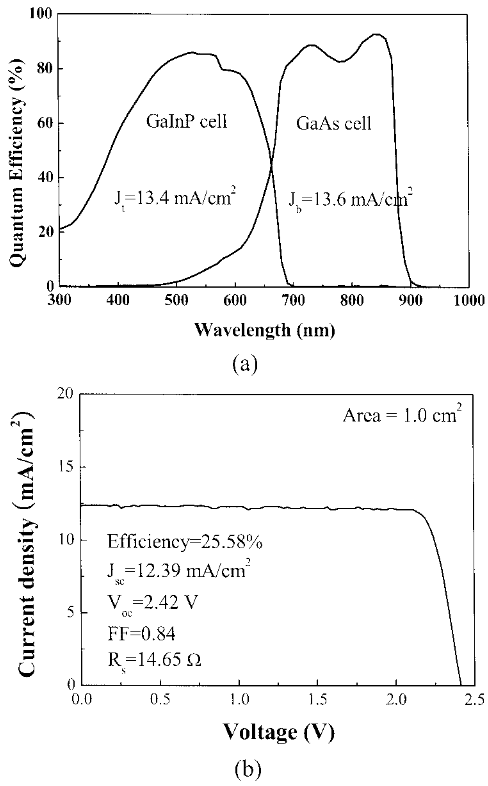


Fig. 8. (a) External quantum efficiency and (b) illuminated current voltage curve of the optimized tandem solar cell with 0.63 μm-thick GaInP top cell.

III. CONCLUSIONS

The effects of the GaAs substrate tilt angles and AlInP window layer growth temperatures on the efficiency performance of GaInP/GaAs two junction tandem solar cells have been investigated. In this experiment, the GaInP/GaAs tandem solar cells with AlInP growth temperatures of 680 ℃ on n-type GaAs (100) substrate with 2° tilt angles exhibits the best efficiency (24.10%) compared with those of 6° tilted GaAs substrate and AlInP growth temperatures of 700 ℃. With the current matching between top and bottom cells, and the carbon as p-type doping source, a GaInP/GaAs tandem solar cell has been exhibited 25.58% efficiency.

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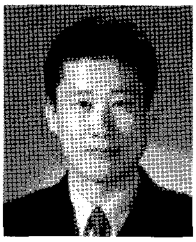

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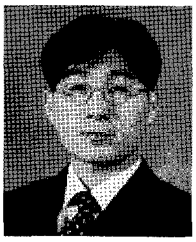

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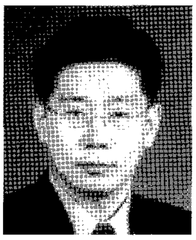

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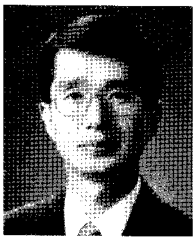

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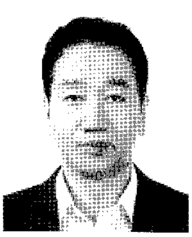

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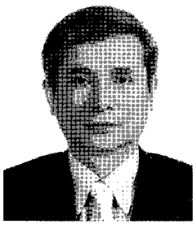

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