High efficiency AlGaAs/Si monolithic tandem solar cell grown by metalorganic chemical vapor deposition

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The improvements of the AlGaAs solar cell grown on the Si substrate and the AlGaAs/Si tandem solar cell by metalorganic chemical vapor deposition have been investigated. The active-area conversion efficiency of the $Al_{0.1}Ga_{0.9}As$ solar cell on the Si substrate as high as 12.9% has been obtained by improving the growth sequence and adopting an Al compositionally graded band emitter layer. A high efficiency monolithic AlGaAs/Si tandem solar cell with the active-area conversion efficiency of 19.9% and 20.6% (AM0 and 1 sun at 27 °C) under two-terminal and four-terminal configurations, respectively, is demonstrated. © *1995 American Institute of Physics.*

I. INTRODUCTION

Tandem structure with more than two junctions has attracted attention for super high efficiency solar cell more than 30%.[1] Recently, InGaP/GaAs tandem solar cell with efficiency as high as 29.5% (AM1.5, 1 sun) has been reported.[2] This was established due to the fact that high quality $In_{0.48}Ga_{0.52}P$ was successfully grown on a GaAs substrate since $In_{0.48}Ga_{0.52}P$ is lattice matched to GaAs. However, GaAs is not a suitable substrate for the practical use of solar cell since it is expensive and fragile. On the other hand, III-V/Si tandem solar cell is one of the suitable material systems to realize a high efficiency solar cell using the advantages of Si, i.e., large area, low cost, light weight, and mechanically strong, etc. Among many III-V compounds, AlGaAs/Si is one of the candidates to obtain an efficiency higher than 30% from the band-gap point of view. However, the fabrication of high efficiency AlGaAs/Si tandem solar cell has not been demonstrated until now. It is still apparently very difficult involving long process times in expensive equipment with toxic gases. The main problem of realizing the high efficiency solar cell is the degradation of the minority-carrier lifetime of AlGaAs layer. This is caused by the high density of dislocation in the AlGaAs layer on Si due to the lattice mismatch and the difference in the thermal expansion coefficient. Moreover, the minority-carrier lifetime is also degraded with the increase of Al composition.[3] In 1992, we reported the preliminary results on the first AlGaAs/Si tandem solar cell.[4] However, the efficiency was 16.3% at AM0 and 1 sun conditions at that time.

This paper describes the improvement of AlGaAs solar cell grown on Si by metalorganic chemical vapor deposition (MOCVD) with varying the growth conditions and the solar cell structure. Moreover, a high efficiency AlGaAs/Si monolithic tandem solar cell higher than 20% is demonstrated for the first time.

II. EXPERIMENT

Epitaxial growth was performed by using conventional atmospheric pressure MOCVD. Trimethylgallium (TMGa), trimethylalluminum (TMAl), diethylzinc (DEZn), AsH_3, and H_2Se were used as the source materials for Ga, Al, Zn, As, and Se, respectively. The Si substrate is Czochralski (Cz) -grown single crystal with the orientation of (100) 2° off towards [011]. GaAs was grown on Si by a two-step growth method with 10-nm-thick GaAs buffer layer grown at 400 °C. First, AlGaAs single-junction solar cell was grown on Si and the conversion efficiency was improved. 1.7-μm-thick n^+-$Al_{0.1}Ga_{0.9}As$ layer ($n=1\times10^{18}$ cm^{-3}), 1.0-μm-thick n-$Al_{0.1}Ga_{0.9}As$ layer ($n=2\times10^{17}$ cm^{-3}), 0.3-μm-thick p^+-$Al_{0.1}Ga_{0.9}As$ layer ($p=1\times10^{18}$ cm^{-3}), 0.05-μm-thick p^+-$Al_{0.8}Ga_{0.2}As$ window layer ($p=1\times10^{18}$ cm^{-3}) and p-GaAs cap layer ($p=5\times10^{18}$ cm^{-3}) were grown on Si sequentially. Antireflection films were made of MgF_2/ZnS double layers. Au-Zn/Au and Au-Sb/Au were evaporated as the p- and n-type electrodes, respectively. The total area of solar cell is 5×5 mm^2 and the photovoltaic characteristics are active-area values under AM0 and 1 sun conditions at 27 °C. The effects of the growth sequence and the graded band emitter layer (GBEL) are described. GBEL was grown instead of 0.3-μm-thick p^+-$Al_{0.1}Ga_{0.9}As$ layer. Two kinds of growth sequences were employed as shown in Fig. 1. It takes approximately 3.5 h for one growth run. *In situ* thermal cycle annealing (TCA) was performed to improve the crystal quality. The differences between sequence (A) and sequence (B) are the growth temperature, the hold time during TCA (5 min) and the peak temperature of TCA. The defect density of the AlGaAs solar cell was evaluated by the electron-beam-induced current (EBIC) image.

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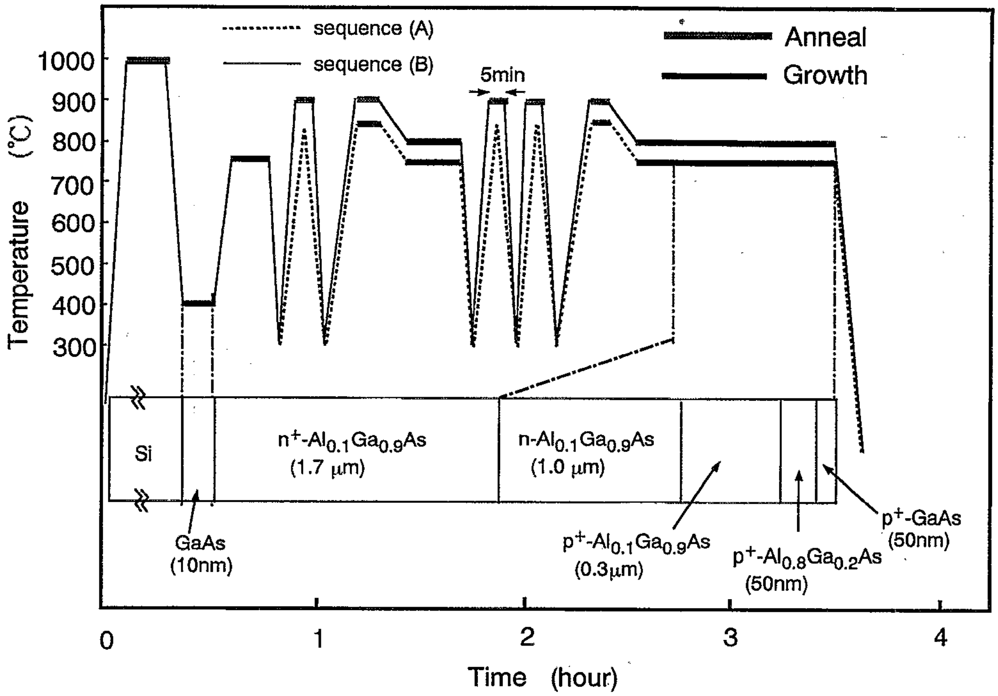

FIG. 1. Sequences (A) and (B) for the growth of AlGaAs solar cell on Si substrate. The cross-sectional schematic structure of single-junction AlGaAs solar cell is shown in the inset.

III. AlGaAs SINGLE-JUNCTION CELL ON Si SUBSTRATE

Table I shows the photovoltaic characteristics, i.e., short-circuit current density (J_{sc}), open-circuit voltage (V_{oc}), fill factor (FF), and conversion efficiency (η), of $Al_{0.1}Ga_{0.9}As$ solar cell grown under sequence (A) and sequence (B). It is shown that J_{sc} and V_{oc} are improved by changing the growth sequence from (A) to (B), resulting in the improvement of the conversion efficiency from 10.2% to 11.5%. Figure 2 shows the quantum efficiency of $Al_{0.1}Ga_{0.9}As$ solar cell grown under sequence (A) and sequence (B). The quantum efficiency at the short-wavelength region is improved with using sequence (B). This improvement is performed by some reasons. First is that the minority-carrier lifetime is improved by increasing the growth temperature, which has been reported in many literatures.[5–7] Second is that the maximum annealing temperature was increased from 850 to 900 °C, which reduces the dislocation density of AlGaAs layer on Si.[8] The EBIC image shows that dark spot density (DSD) is reduced from 1.6×10^7 to 1.1×10^7 cm^{-2}. The increase of conversion efficiency for GaAs/Si tandem solar cell at high annealing temperature has already been reported by the present authors.[9] Third is that the sample was annealed at 900 °C for 5 min at each TCA. It has been reported that it takes more than 5 min to achieve an equilibrium in vacancy concentration, which is necessary for the reduction of threading dislocation density effectively.[8] The threading dislocations are reduced by the compressive stress at the temperature higher than the growth temperature. The detailed photovoltaic characteristics with various growth conditions are reported elsewhere.

In order to increase the conversion efficiency furthermore, we adopted the GBEL structure. It is expected that the

TABLE I. Photovoltaic characteristics of $Al_{0.1}Ga_{0.9}As$ solar cell on Si substrate.

Sample	J_{sc}(mA/cm^2)	V_{oc} (V)	FF (%)	η (%)
Sequence (A) without GBEL	21.3	0.905	71.6	10.2
Sequence (B) without GBEL	24.5	0.918	69.8	11.5
Sequence (B) with GBEL	25.2	0.929	81.6	12.9

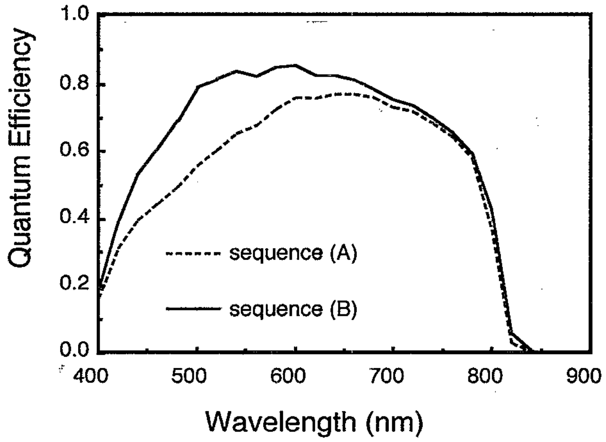

FIG. 2. Quantum efficiency of $Al_{0.1}Ga_{0.9}As$ single-junction cell grown under sequence (A) and sequence (B).

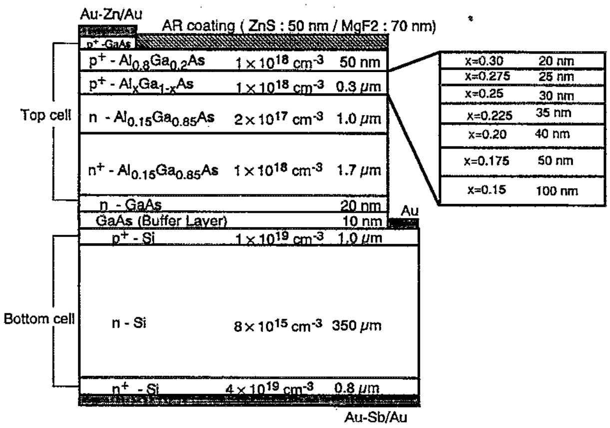

FIG. 3. Cross-sectional schematic illustration of AlGaAs/Si tandem solar cell.

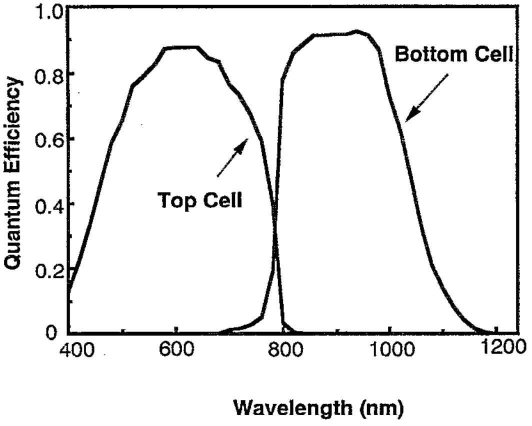

FIG. 5. Quantum efficiency of AlGaAs/Si tandem solar cell with GBEL.

conversion efficiency is increased due to the increase of carrier collection efficiency by the internal field. In this study, we fabricated the internal field by growing a p-type Al compositionally step graded band emitter layer between the p-type $Al_{0.8}Ga_{0.2}As$ window layer and n-type $Al_{0.1}Ga_{0.9}As$ layer. The Al composition and the thickness of the individual layer are (0.1, 0.1 μm), (0.125, 40 nm), (0.15, 30 nm), (0.175, 30 nm), (0.2, 30 nm), (0.225, 30 nm), (0.25, 20 nm), and (0.27, 20 nm), respectively. The sequence (B) was used for the crystal growth. The photovoltaic characteristics of AlGaAs solar cell with GBEL are also shown in Table I. The conversion efficiency, J_{sc} and V_{oc} are improved with utilizing GBEL, and the conversion efficiency as high as 12.9% has been obtained.

IV. AlGaAs/Si TANDEM SOLAR CELL

The AlGaAs/Si monolithic tandem solar cell was fabricated by employing the graded band emitter layer and using the growth sequence (B). Prior to the growth, p^+-n junction was formed in Cz-grown Si substrate ($n=8\times10^{15}$ cm^{-3}) by B diffusion in O_2+N_2 atmosphere at 1000 °C, followed by the formation of n-n^+ back surface field by P diffusion in N_2 atmosphere at 900 °C. The schematic view of the cross section including the individual layer thickness and the carrier concentration is shown in Fig. 3. $Al_{0.15}Ga_{0.85}As$ was grown instead of $Al_{0.1}Ga_{0.9}As$ for the current matching between the top cell and the bottom cell. After the growth, the electrodes for p-GaAs, p-Si, and n-Si were formed by evaporating Au-Zn/Au, Au, and Au-Sb/Au, respectively. The top cell was connected with the bottom cell by n^+-GaAs/p^+-Si heterojunction. The current-voltage characteristics of this junction show ohmic relation.[10]

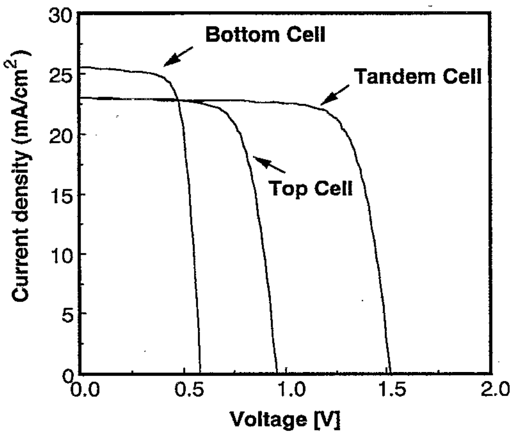

FIG. 4. Current density-voltage characteristics of AlGaAs/Si tandem solar cell.

Figure 4 shows the current density-voltage characteristics for the top cell, the bottom cell, and the two-terminal tandem cell. It is shown that the current density of the top cell is almost matched to that of bottom cell. Figure 5 shows the quantum efficiency for the top cell and bottom cell. The detailed photovoltaic characteristics of the tandem cell are summarized in Table II. The conversion efficiencies of 19.9% and 20.6% have been obtained at AM0 and 1 sun conditions with the two-terminal and four-terminal configurations, respectively. As far as we know, this is the highest efficiency for III-V/Si monolithic tandem solar cell as reported before.

It has been pointed out that the high efficiency two-terminal tandem solar cell higher than 30% can be obtained by using the top cell material with the band-gap energy of 1.7–1.8 eV with Si bottom cell under two-terminal configuration.[1] It resulted in the current matching between the top cell and the bottom cell. However, in our study, the current matching was done by using the $Al_{0.15}Ga_{0.85}As$ top cell, of which the band-gap energy is 1.61 eV. This is due to

TABLE II. Photovoltaic characteristics of $Al_{0.15}Ga_{0.85}As$/Si monolithic tandem solar cell with GBEL.

		J_{sc}(mA/cm^2)	V_{oc} (V)	FF (%)	η (%)
Top cell		23.0	0.953	73.4	11.9
Bottom cell		25.8	0.579	79.1	8.72
Tandem cell	(two-terminal)	23.0	1.51	77.2	19.9
	(four-terminal)				20.6

that the short-circuit current of the top cell is inferior to the ideal one. The main reason for the degradation is mainly due to the high density of dislocation in the AlGaAs layer on Si. The dark spot density of EBIC image for AlGaAs layer is 1.1×10^{7} cm^{-2} at present, which degrades the short-circuit current and the open-circuit voltage. If it becomes possible to grow low-dislocation-density AlGaAs layer on Si substrate comparable to that grown on GaAs substrate, we can obtain higher efficiency tandem solar cell by increasing the Al composition so that the current matching between the top cell and the bottom cell is performed.

The improvement of the Si bottom cell is also important for the increase of the total conversion efficiency. The main problem is that the conversion efficiency is degraded after the crystal-growth process,[9] although the crystal quality of Si wafer before the growth is sufficiently high with the minority carrier diffusion length longer than 100 μm. The junction depth becomes deeper and the As atoms diffuse into the Si substrate during the growth.[9] The low-temperature growth process is necessary for the improvement of the bottom cell.

V. CONCLUSION

The improvement of AlGaAs solar cell grown on Si substrate using proper growth sequence and GBEL, and the fabrication of AlGaAs/Si monolithic tandem solar cell have been described. The conversion efficiency of single-junction $Al_{0.1}Ga_{0.9}As$ solar cell on Si as high as 12.9% has been obtained by using the improved growth sequence and the use of GBEL. AlGaAs/Si tandem solar cell with the active area efficiencies of 19.9% and 20.6% has been obtained under AM0 and 1 sun conditions under the two-terminal and four-terminal configurations, respectively.

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