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High Efficiency Monolithic GaAs/Si Tandem Solar Cell Grown by Metalorganic Chemical Vapor Deposition

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The monolithic GaAs/Si tandem solar cell which consists of p^+-n GaAs top cell and n^+-p-p^+ Si bottom cell is fabricated by metalorganic chemical vapor deposition. The conversion efficiency of the top cell is increased by adopting graded band emitter layer and improving the thermal annealing temperature and the growth temperature. Combining the conversion efficiencies of GaAs top cell (16.0 %) and Si bottom cell (3.9 %), the active-area conversion efficiency of 19.9 % (AM0, 1sun) has been obtained in three-terminal configuration.

1. INTRODUCTION

A monolithic tandem solar cell is very attractive to achieve high conversion efficiency photovoltaic cell since it produces a wider photovoltaic spectral response compared with a single junction cell. Until now, tandem solar cells such as AlGaAs/GaAs[1] and GaInP/GaAs[2] have been demonstrated, which are lattice-matching material system.

The advantages of GaAs/Si tandem solar cell are not only that the theoretical conversion efficiency is higher than 30% but also that the substrate is low-cost, light weight, large-area and mechanically strong. However, in this material system, high density of dislocations is generated due to the lattice mismatch and/or thermal expansion mismatch, which degrades the minority carrier lifetime. It results in the decrease of the conversion efficiency.

In the previous paper, we reported the three-terminal GaAs/Si tandem solar cell with the conversion efficiency of 19.1% (AM0, 1sun) by optimizing the resistivity of the Si substrate[3].

This paper describes the improvement of GaAs/Si tandem solar cell by adopting graded band emitter layer (GBEL) and by varying the thermal cycle annealing (TCA) conditions and growth temperature.

2. EXPERIMENTAL

The epitaxial growth was performed by atmospheric pressure metalorganic chemical vapor deposition (MOCVD). The substrate is p-type 350 μm-thick (100) Cz-grown silicon wafers tilted 2° toward [011] with the resistivity of 1.6 Ωcm. The Si n^+-p-p^+ structure was formed with P thermal diffusion at 900 °C and B thermal diffusion at 1000 °C by spin-coating method. The carrier concentration and the depth of n^+ Si are 1.2×10^{19} cm^{-3} and 1.1 μm, respectively. Those of p^+ Si are 1.4×10^{19} cm^{-3} and 0.5 μm, respectively.

p^+n AlGaAs/GaAs solar cell was grown on Si solar cell using two-step growth method. The schematic cross-sectional structure of GaAs/Si tandem solar cell is shown in Fig. 1. A GBEL was grown between $Al_{0.8}Ga_{0.2}As$ window layer and p-type GaAs emitter layer. Al composition of GBEL was varied linearly from 0 to 0.29.

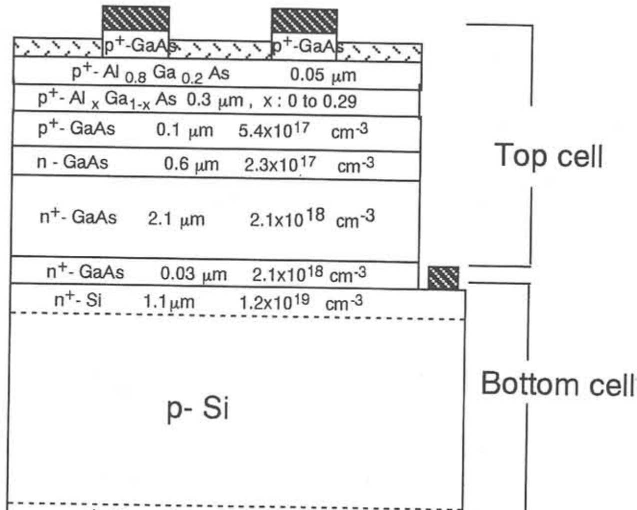

Fig. 1 Structure of GaAs/Si tandem solar cell.

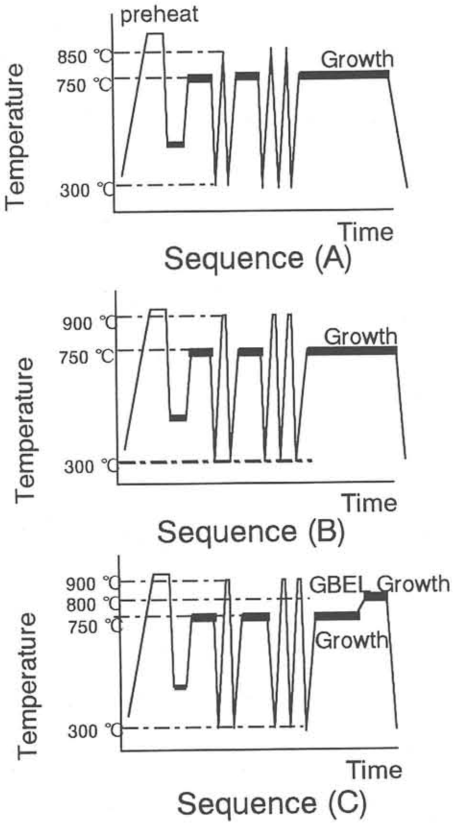

Fig. 2 Growth sequences for epitaxial growth.

In order to improve the crystal quality of the heteroepitaxial layer, three kinds of growth sequence were employed. The respective growth sequences are shown in Fig. 2. The main differences are thermal cycle annealing temperature and the growth temperature of AlGaAs layer. The output electrodes for p^+-GaAs, n^+-Si and p^+-Si are Au/AuZn, Au/AuSb and Au, respectively. The double antireflection films consist of ZnS and MgF_2 films deposited by electron beam evaporation. The area of solar cell is 5 x 5 mm^2. The photovoltaic properties were measured under AM0 and 1 sun conditions at 27 °C. The conversion efficiency is active-area value.

3. RESULTS AND DISCUSSION

Because of the existence of high-dislocation density in GaAs layer on Si, which degrades the lifetime of photo-generated carriers, GaAs solar cell on Si substrate has a lower conversion efficiency in comparison with GaAs solar cell on GaAs substrate. We used two methods to improve the conversion efficiency in this study.

One method is to use the electric field to collect the carriers. Inserting a graded band emitter layer of $Al_xGa_{1-x}As$ between the $Al_{0.8}Ga_{0.2}As$ window layer and the p-GaAs emitter layer (Al content of $Al_xGa_{1-x}As$ is varied linearly with the distance), it provides an electric field in the p-active region to enhance the collection of photo-generated carriers rather than the recombination. The Al mole fraction at the surface of GBEL is chosen to be 0.29, because the diffusion length[4], the electron mobility[5] and the lifetime[6] do not strongly depend on Al composition of $Al_xGa_{1-x}As$ in the range $x<0.3$. GBEL in the p-$Al_xGa_{1-x}As$ active layer will produce a strong electric field and the carrier collection efficiency is effectively enhanced because the effect of the bulk and interface recombination are reduced.

Another method is to improve the crystal quality of GaAs on Si substrate by reducing the dislocation density or interface recombination velocity.

Fig. 3 shows the quantum efficiencies of GaAs solar cell with and without GBEL for various growth sequences. The quantum efficiency of the GaAs top cell is improved clearly with GBEL in the wavelength range from 460 nm to 860 nm compared with the GaAs top cell on Si without the GBEL. This figure also indicates that the quantum efficiency of the solar cell with TCA (300°C - 900°C) is higher than that with TCA (300°C - 850°C). This is due to the reduction of the dislocation density of GaAs layer at higher TCA temperature. The transmission electron microscopy measurement shows that most threading dislocations are bent near the GaAs/Si interface in the case of TCA (300°C - 900°C), whereas most dislocations are propagated towards the surface in the case of TCA (300°C - 850°C). The electron beam induced current image shows that the dark spot defect density of the best sample is 6.3 x 10^6 cm^{-2}.

When the GBEL of AlGaAs is grown at the temperature of 800 °C, the quantum efficiency is improved further. This is due to that the crystallinity of AlGaAs layer is improved at higher growth temperature.

Table I shows short circuit current (Jsc), open circuit voltage (Voc), fill factor (FF) and conversion efficiency

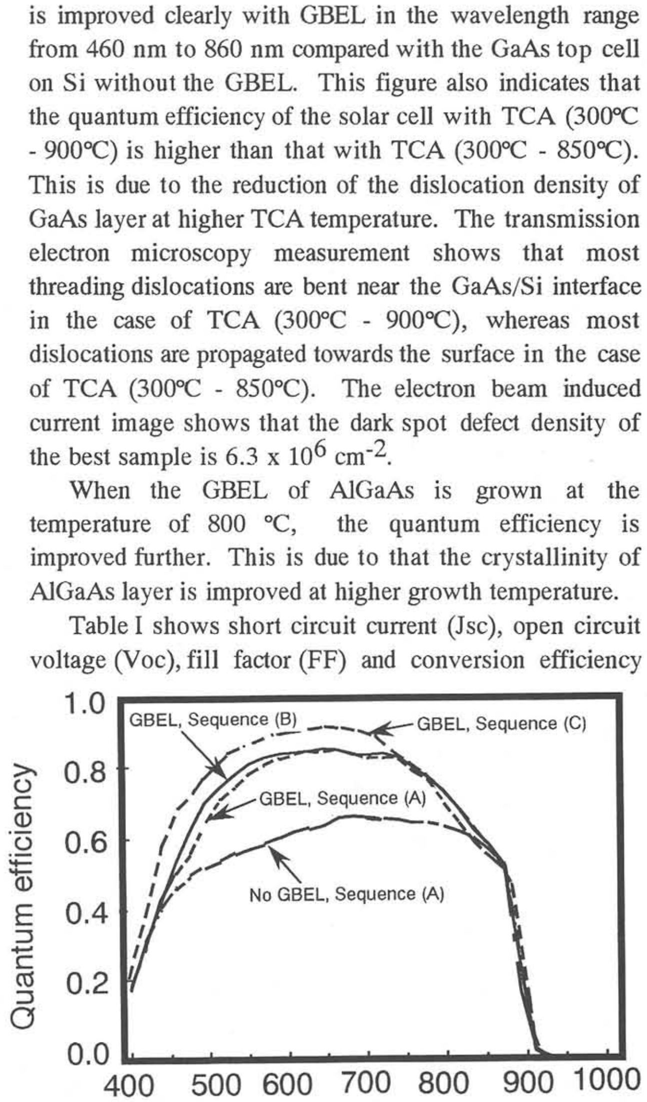

Fig. 3 Quantum efficiency of GaAs solar cell on Si.

Table I Photovoltaic properties of GaAs solar cell on Si.

Growth sequence	(mA/cm^2) Jsc	(V) Voc	(%) FF	(%) η
No GBEL, Sequence (A)	21.1	0.820	76.8	11.6
GBEL , Sequence (A)	29.8	0.825	76.2	13.9
GBEL , Sequence (B)	30.7	0.857	77.9	15.1
GBEL , Sequence (C)	33.9	0.849	75.0	16.0

(η) of the solar cell with various growth sequences. From this table, it can be seen that GBEL is only effective for improving the carrier collection efficiency and it results in the increase of Jsc. The effect is not observed for Voc, which is still limited by the high-dislocation density. The dislocations in GaAs epitaxial layer on Si not only degrade the lifetime of the minority carriers but also increase the dark-current of the GaAs top solar cell, which results in lower Voc. Combining TCA (300°C - 900°C) and the high temperature growth of the GBEL, the conversion efficiency of the GaAs top cell as high as 16.0 % has been achieved.

Current-voltage characteristics of GaAs top cell and Si bottom cell under AMO and 1 sun conditions are shown in Fig. 4. The total conversion efficiency of 19.9 % has been achieved by combining the efficiency of GaAs top cell (η=16.0%, Jsc=33.9 mA/cm^2, Voc=0.849 V, FF=75.0%) and Si bottom cell (η=3.9%, Jsc=13.7 mA/cm^2, Voc=0.520 V, FF=74.0%) in three-terminal configuration. As far as we know, this is the highest efficiency for the GaAs/Si monolithic tandem solar cell as ever reported before.

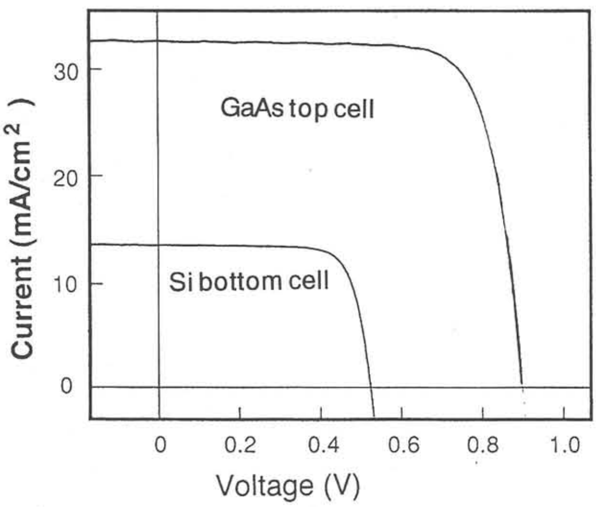

Fig. 4 Current-voltage characteristics of GaAs/Si tandem solar cell.

4. CONCLUSION

The improvement of GaAs/Si three-terminal monolithic tandem solar cell grown by MOCVD has been studied. Using the GBEL structure, the short circuit current density was drastically increased. The active-area efficiency of 19.9 % (AM0, 1sun) has been obtained by increasing the maximum TCA temperature (from 850 °C to 900 °C) and the AlGaAs growth temperature (from 750 °C to 800 °C).

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