Photovoltaic properties of an $Al_xGa_{1-x}As$ solar cell ($x=0-0.22$) grown on Si substrate by metalorganic chemical vapor deposition and thermal cycle annealing

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The effects of a thermal cycle annealing (TCA) process on the defects in GaAs and $Al_xGa_{1-x}As$ solar cells on Si substrates are described in this paper. The defect density is reduced and the solar cell efficiency is improved by TCA. The defect density and the solar cell efficiency are evaluated in detail with respect to TCA temperature and Al composition. The problems involved in the fabrication of a high efficiency AlGaAs solar cell on a Si substrate are discussed. © *1996 American Institute of Physics.* [S0021-8979(96)03712-7]

I. INTRODUCTION

Recently, high efficiency solar cells have been studied actively for future photovoltaic systems. A tandem solar cell including more than two junctions is one of the candidates for the photovoltaic cell, having a conversion efficiency higher than 30%. Among many material systems, the two-terminal AlGaAs/Si monolithic tandem solar cell is attractive for its high efficiency, low cost and large-area photovoltaic cell from the band-gap-energy point of view.[1] It has been calculated that a conversion efficiency higher than 33% can be obtained with $Al_{0.22}Ga_{0.78}As$ as the top cell and Si as the bottom cell.[2] The problem with high efficiency solar cell fabrication is the difficulty in growing AlGaAs on a Si substrate with long minority carrier lifetime. This results from the generation of defects in the $Al_{0.22}Ga_{0.78}As$ layer due to lattice mismatch, difference in the thermal expansion coefficients, the creation of Al-O or Al-C related defects, etc. In a previous paper, we reported an AlGaAs/Si tandem solar cell with a conversion efficiency as high as 20.6% at AM0 and 1 sun.[3] However, this value is much lower than the theoretical value. In order to improve the conversion efficiency, it is necessary to study the relationship between the solar cell efficiency and the crystal quality of the AlGaAs layer grown on Si substrates.

Until now, it has been generally known that the thermal cycle annealing (TCA) is effective in reducing the dislocation density of GaAs on Si substrate.[4,5] However, there were only few reports about the effectiveness of TCA on reducing the dislocation density in an AlGaAs alloy grown on a Si substrate.[3] This paper describes the defect reduction and the conversion efficiency improvement of GaAs and AlGaAs solar cells grown on a Si substrate with annealing temperature and Al alloy composition.

II. EXPERIMENT

Epitaxial growth was performed by using conventional atmospheric pressure metalorganic chemical vapor deposition (MOCVD). Trimethylgallium (TMG), trimethylallumінum (TMA), and AsH_3 were used as the source materials for Ga, Al, and As, respectively. Diethylzinc (DEZ) and H_2Se were p-type and n-type dopants, respectively. The substrate orientation was (001) 2° off toward [110]. The growth conditions and the solar cell structure were almost the same as reported previously.[3] After forming a pn junction in the Si substrate, a GaAs solar cell or AlGaAs solar cell was fabricated. Although the AlGaAs/Si tandem solar cell was fabricated in the present study, we report only the characteristics of an AlGaAs top cell. The detailed characteristics of an AlGaAs/Si tandem solar cell will be reported elsewhere. A 1.7-μm-thick n^+ $Al_xGa_{1-x}As$ ($n=2.1\times10^{18}$ cm^{-3}), 1.0 μm $Al_xGa_{1-x}As$ ($n=2.3\times10^{17}$ cm^{-3}), 0.3 μm $Al_yGa_{1-y}As$ ($p=1\times10^{18}$ cm^{-3} and graded Al composition y was from x to 0.29) and 50-nm p^+-$Al_{0.8}Ga_{0.2}As$ window layer were grown sequentially. The Al composition x was varied between 0 and 0.22. The growth temperatures of GaAs and AlGaAs were 750 °C and 800 °C, respectively, unless otherwise mentioned. The detailed solar cell structure is shown in Fig. 1. TCA was performed five times during growth of the n^+-type AlGaAs layer. The TCA sequences were as follows; after the initial growth of 0.7-μm-thick n^+ AlGaAs layer, TCA was performed twice, followed by the growth of a 0.7 μm AlGaAs layer. TCA was then performed three times before the final growth of a 0.3 μm n^+ AlGaAs layer. The maxima of the TCA temperature was varied from 850 to 1000 °C, and the minimum temperature was kept constant at 300 °C. The total area of the fabricated solar cell was 5×5

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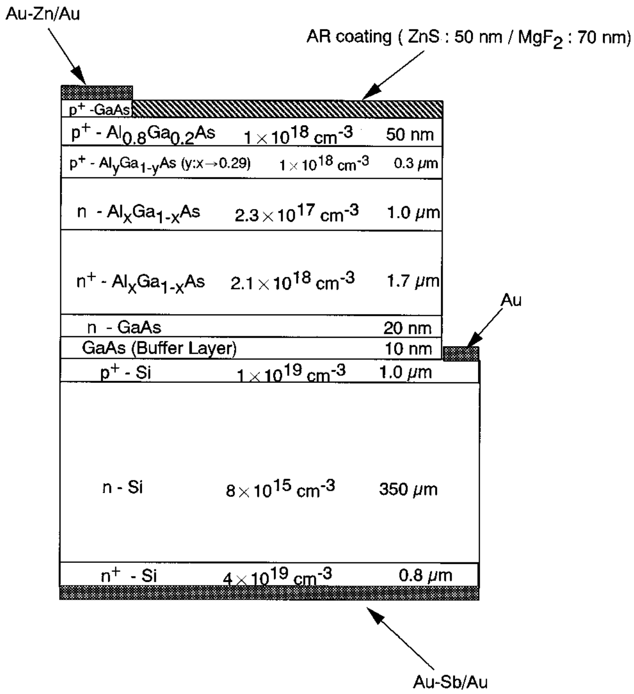

FIG. 1. Schematic cross-sectional view of the AlGaAs/Si tandem solar cell.

mm^2 and the photovoltaic properties were active-area values under AM0 and 1 sun at 27 °C. The total area efficiency is 0.882× the active area efficiency. The solar cell has been evaluated by dark spot density (DSD) of electron beam induced current (EBIC) image, cross-sectional transmission electron microscopy (TEM), and secondary ion mass spectroscopy (SIMS).

III. RESULTS

When GaAs or AlGaAs is grown on a Si substrate, the defects which are not desirable for a solar cell are generated. Defects such as dislocations become recombination centers, which results in the degradation of the solar cell efficiency.

First, a GaAs solar cell ($x=0$) is fabricated on a Si substrate by changing TCA temperature. Figure 2 shows the DSD and the conversion efficiency (η) of the GaAs top cell for various TCA temperatures. A TCA of 750 °C means that the TCA is not performed. The DSD decreases with increasing maxima of the substrate temperature. Accordingly, the conversion efficiency increases with increasing temperature. The DSD of GaAs on Si as low as 6.3×10^6 cm^{-2} and the conversion efficiency as high as 15.1% have been achieved only by the TCA process.

Since the GaAs solar cell is not suitable for the top cell of the two-terminal tandem cell, the $Al_xGa_{1-x}As$ solar cell is fabricated by changing the Al composition x. Figure 3 shows the DSD and the ratio of the experimentally obtained conversion efficiency η to the theoretical efficiency η_{theory} as a function of x. The maxima of the TCA temperature is 850 °C and 900 °C. In this figure, the ratio of conversion efficiency is chosen as the scale of the vertical axis because the theoretical efficiency decreases with increasing x. The DSD is reduced and the conversion efficiency ratio is increased at all the Al compositional range when the TCA temperature increased from 850 to 900 °C. However, the DSD increases with increasing Al composition and the DSD of the $Al_{0.22}Ga_{0.78}As$ solar cell on Si is still higher than 10^7 cm^{-2} after the TCA process, although the DSD of the GaAs solar

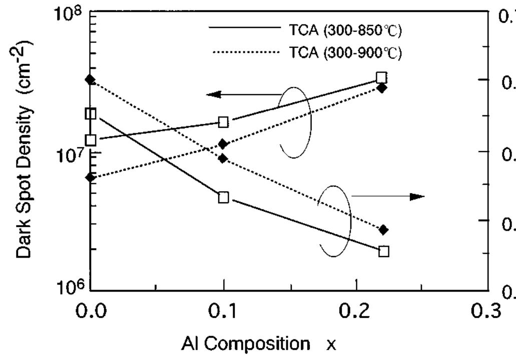

FIG. 3. Conversion efficiency ratio and DSD of an AlGaAs solar cell as a function of Al composition. The dark spot density is increased and the efficiency is degraded with increasing Al composition.

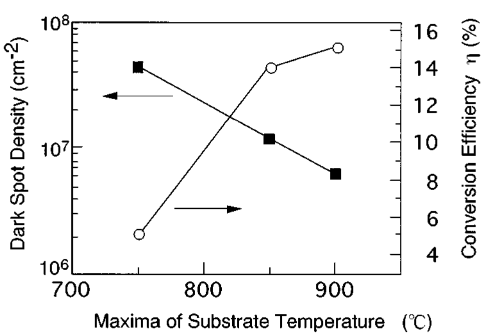

FIG. 2. Conversion efficiency and DSD of the GaAs solar cell as a function of the maxima of substrate temperature. The conversion efficiency is improved and the dark spot density is reduced at higher TCA temperature. The lowest dark spot density is 6.3×10^6 cm^{-2}.

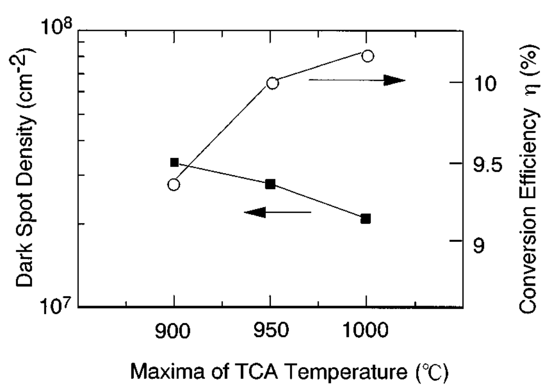

FIG. 4. Conversion efficiency and DSD of an $Al_{0.22}Ga_{0.78}As$ solar cell as a function of the maxima of TCA temperature. The conversion efficiency is improved and the dark spot density is reduced at higher TCA temperature. The lowest dark spot density is still on the order of 10^7 cm^{-2}.

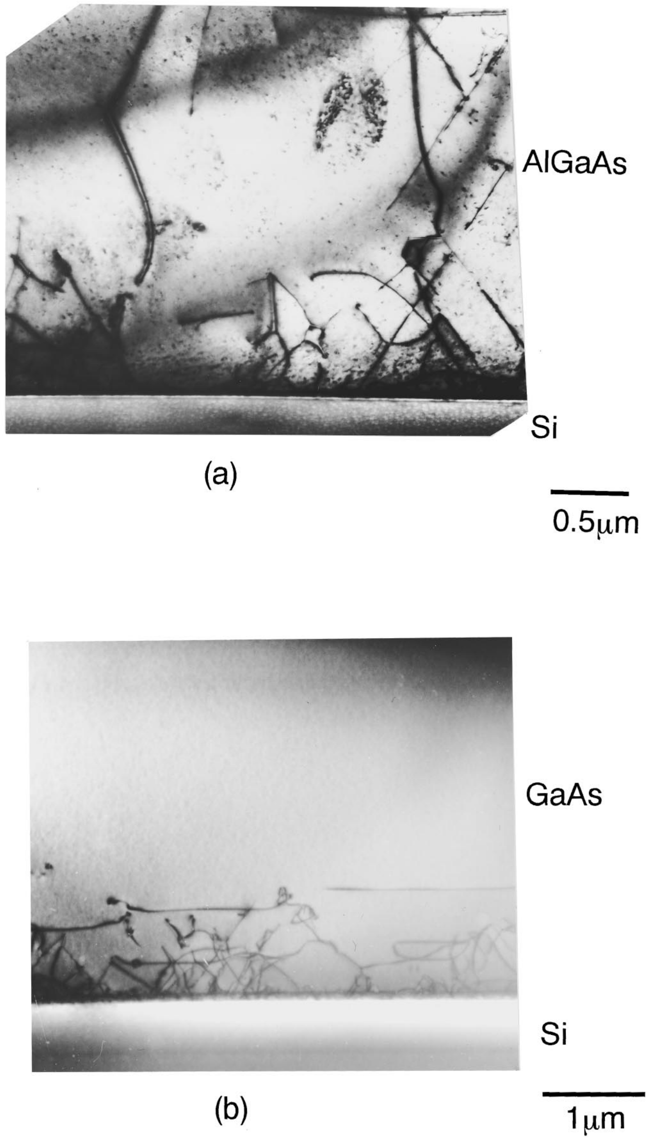

FIG. 5. Cross-sectional TEM micrographs of an $Al_{0.15}Ga_{0.85}As$ solar cell on Si (a) and GaAs solar cell on Si (b). High density of dislocation is observed in (a), whereas most of the dislocations are bent near the interface in (b).

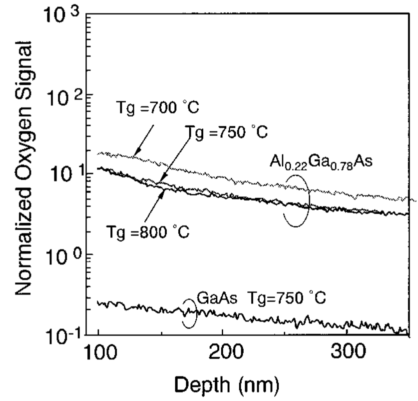

FIG. 6. SIMS in-depth oxygen concentration profile of an $Al_{0.22}Ga_{0.78}As$ solar cell and GaAs solar cell grown on Si substrates at various growth temperature. Growth temperature is varied from 700 to 800 °C.

cell on Si is on the order of 10^6 cm^{-2} after the TCA process at 900 °C. Therefore, the conversion efficiency drastically decreases with increasing Al composition x.

In order to reduce the dislocation density further, the TCA was performed at higher temperature. The DSD of $Al_{0.22}Ga_{0.78}As$ on Si and the solar cell efficiency η are shown in Fig. 4 as a function of TCA temperature. The DSD is reduced and the efficiency is increased gradually with increasing temperature. However, the DSD is still on the order of 10^7 cm^{-2} even after the 1000 °C TCA.

In order to compare the defect structure of a GaAs solar cell and the AlGaAs solar cell grown on a Si substrate, the samples are evaluated by cross-sectional TEM. The TEM micrographs of the AlGaAs solar cell and GaAs solar cell grown on a Si substrate are shown in Figs. 5(a) and 5(b), respectively. The TCA temperature is 900 °C and the Al composition of the AlGaAs solar cell is 0.15. The dislocations in GaAs are bent parallel to the (001) plane near the GaAs/Si interface. On the other hand, most of the dislocations propagate toward the surface in the case of the AlGaAs solar cell. It means that the TCA is not so effective on dislocation reduction for AlGaAs-on-Si as compared to GaAs-on-Si.

Figure 6 shows the in-depth SIMS profile of normalized oxygen concentration of an AlGaAs solar cell and GaAs solar cell grown at various temperatures. The oxygen concentration of AlGaAs slightly decreases with increasing growth temperature. However, the oxygen concentration of AlGaAs on Si is more than one order of magnitude higher than that of GaAs on Si.

IV. DISCUSSION

The problems in fabricating a high efficiency $Al_{0.22}Ga_{0.78}As$ solar cell on Si are discussed because $Al_{0.22}Ga_{0.78}As$ has a suitable band gap energy and current matching for the top cell of the III–V/Si tandem solar cell.

As shown in Fig. 2, the DSD of GaAs grown on a Si substrate decreases to the level of 6.3×10^6 cm^{-2} only by the TCA at 900 °C. The decrease of DSD at higher temperature is due to the following two reasons. One is that at high temperature the motion of dislocation is promoted and the probability of two dislocations to combine and annihilate increases. The other reason is that the larger compressive stress due to the difference in the thermal expansion coefficients is applied at higher temperature. The climb of pure edge dislocations toward the interface is enhanced at higher compressive stress. It results in the lower threading dislocation density in the epitaxial layer. The GaAs solar cell with the conversion efficiency as high as 15.1% ($\eta/\eta_{theory}=0.59$) has been achieved only by the TCA process.

On the other hand, the conversion efficiency of the AlGaAs solar cell is degraded with increasing Al composition x (see Fig. 3). One reason for the degradation is the existence of a high density of dislocation in the AlGaAs layer even after the TCA process. The DSD of $Al_{0.22}Ga_{0.78}As$ is still on the order of 10^7 cm^{-2} even after the TCA at

1000 °C. The TEM micrographs clearly show the difference of the effectiveness of TCA for GaAs-on-Si and AlGaAs-on-Si (Fig. 5).

Another reason for the degradation of the efficiency is the incorporation of high density of oxygen into the AlGaAs layer compared to the GaAs layer due to a strong Al-O bond. The conversion efficiency is reduced by the short minority carrier lifetime due to the nonradiative Al-O related defects.[6,7]

It is concluded that the main reasons for the low conversion efficiency of the AlGaAs solar cell are the high dislocation density and high oxygen concentration. The reduction of dislocation density and oxygen concentration in the AlGaAs solar cell is necessary for further improvement of the conversion efficiency.

V. SUMMARY

The defect density reduction of GaAs and AlGaAs solar cells grown on a Si substrate by the TCA process has been described in this paper. The TCA process was found to be effective in reducing the defect density of a GaAs solar cell grown on Si and improving the conversion efficiency. On the other hand, the conversion efficiency of AlGaAs was decreased with increasing Al composition. The TCA process for the AlGaAs solar cell on Si was not effective as the GaAs solar cell on Si. The higher efficiency could be achieved by decreasing the dislocation density and the oxygen concentration of the AlGaAs epitaxial layer.

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