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Post-annealing Effects on Characteristics of Crystalline Germanium Solar Cells with the Double Heterostructure

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1. Introduction

To realize solar cells with high conversion efficiency, solar cells which can absorb the long wavelength light are desired. Germanium is a suitable material to fabricate solar cells for this aim due to its low energy band gap. One of the applications of Ge solar cells is a bottom cell for the mechanically stacked solar cells. The mechanically stacked solar cells have advantages that individual solar cells can be optimized more easily than conventional multi-junction solar cells without any constraint of lattice matching, while conventional four or six terminal cells are difficult to incorporate into an integrated module.

On the other hand, crystalline silicon (c-Si) heterojunction solar cells with hydrogenated amorphous silicon (a-Si:H) have proven to be beneficial for higher efficiency over conventional c-Si solar cells. This is because excellent passivation ability leads to high open-circuit voltage. We previously demonstrated that a-Si:H is also a suitable material for crystalline germanium (c-Ge) heterojunction solar cells [1].

In this study, we fabricated a-Si:H/c-Ge heterojunction solar cells with a double heterostructure (DH) to improve the conversion efficiency. In addition, effects of post-annealing on characteristics of a-Si:H/c-Ge DH solar cells were investigated.

2. Experimental

For fabrication of solar cells in this study, p-type Ge(111) substrates with a resistivity of 0.015 Ω·cm were used. The structure of a-Si:H/c-Ge solar cells with a double heterostructure (DH) is Ag grid/In_2O_3:Sn (70 nm)/a-Si:H n layer (6 nm)/a-Si:H i layer (13 nm)/p-type c-Ge (400 μm)/a-Si:H i layer (4 nm)/a-Si:H p layer (15 nm)/ In_2O_3:Sn (70 nm)/Al. In solar cells with single heterostructure (SH), the Al electrode was deposited directly on the back side of the c-Ge substrate. The a-Si:H layers were deposited by plasma-enhanced chemical vapor deposition (PECVD) method. The undoped a-Si:H layer was deposited using pure SiH_4 gas. The n-type a-Si:H layer was deposited using SiH_4, H_2, and PH_3 mixture gases with the flow rate ratio of [PH_3/SiH_4] = 4.0 vol%. Meanwhile, The p-type a-Si:H layer was deposited using SiH_4, H_2, and B_2H_6 mixture gases with the flow rate ratio of [B_2H_6/SiH_4] = 6.7 vol%. The deposition temperature of the a-Si:H layers was 150 °C. For the cleaning of the c-Ge substrates, the native oxide was removed by 10 % HF solution followed by the intentional oxidation by H_2O_2 solution. The surface oxide was removed inside the vacuum chamber by a flashing treatment at 450 °C for 20 min [1]. By using a substrate-flipping mechanism which is directly connected to the vacuum-transfer system, all a-Si:H layers deposition was performed without exposure to the air.

To investigate the surface passivation ability of a-Si:H for c-Ge, a sample of the c-Ge substrate having a-Si:H i layers on both side was prepared. In this experiment, the c-Ge substrate with the resistivity of 2.5 Ω·cm was used. The carrier lifetime was measured by a microwave-detected photoconductance decay (μ-PCD) method.

In this study, the post-annealing for the a-Si:H/c-Ge solar cells and the a-Si:H i layer/c-Ge/a-Si:H i layer sample was performed in vacuum at 100 to 240 °C for 2 hours.

3. Results and Discussion

Figure 1 shows current density versus voltage for the a-Si:H/c-Ge SH and DH solar cells. The SH solar cell with the efficiency of 4.40 % (an open-circuit voltage (V_{OC})=0.242 V, a short-circuit current density (J_{SC})=39.5 mA/cm^2, a fill factor (FF)=0.460) was obtained. In the DH solar cell, the efficiency increases to 4.87 % (V_{OC}=0.243 V, J_{SC}=41.6 mA/cm^2, FF=0.482). The improvement of efficiency is attributed to the increase of J_{SC} and FF. On the other hand, V_{OC} of the DH and SH solar cells are almost the same. Figure 2 shows external quantum efficiency (EQE) spectra of the a-Si:H/c-Ge SH and DH solar cells. The solar cells in Fig. 2 correspond to that shown in Fig. 1. The EQE response of DH solar cell improves in the whole spectral range.

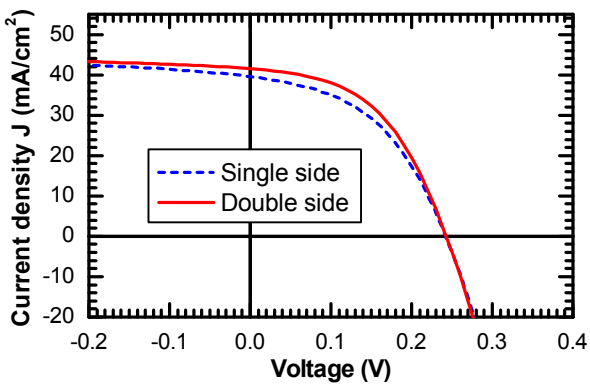

Fig. 1 Current density versus voltage for the a-Si:H/c-Ge SH and DH solar cells.

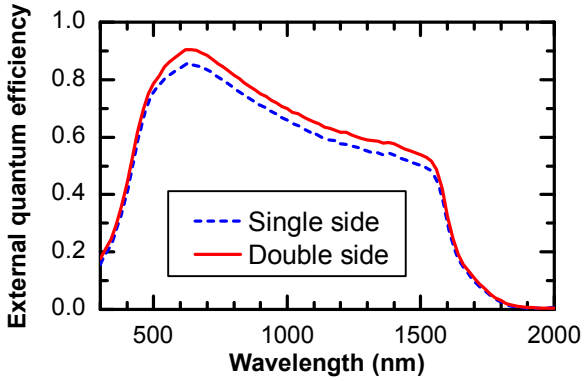

Fig. 2 External quantum efficiency spectra of the a-Si:H/c-Ge SH and DH solar cells

Figure 3 shows characteristics of a-Si:H/c-Ge SH and DH solar cells as a function of annealing temperature (T_a). In the DH solar cell, V_{OC} decreases with increasing T_a up to 150 °C, then it increases at T_a > 150 °C. On the other hand, J_{SC} and FF increase with increasing T_a, and decrease at T_a > 200 °C. The decrease of FF at T_a > 200 °C as shown in Fig. 3 was mainly caused by the increase of the series resistance (not shown here). As a result, maximum efficiency of a-Si:H/c-Ge heterojunction solar cells was obtained at T_a = 200 °C. This optimum T_a is relatively high compared to the T_a = 140 °C of c-Si-based heterojunction solar cells [2].

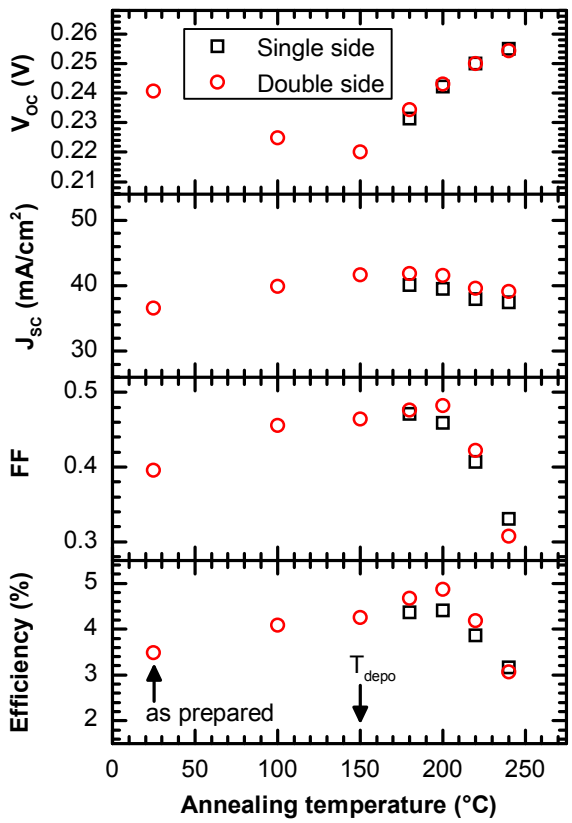

Fig. 3 Characteristics of a-Si:H/c-Ge SH and DH solar cells as a function of annealing temperature.

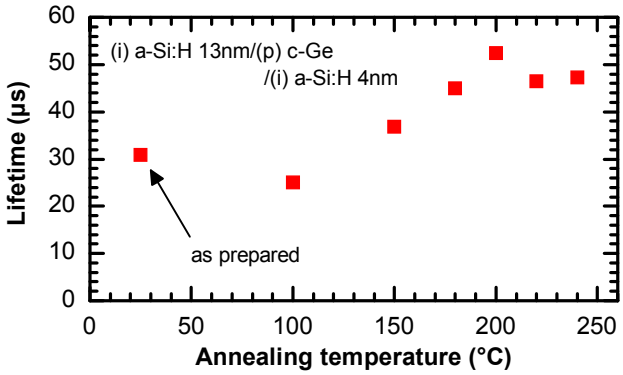

Fig. 4 Carrier lifetime of a-Si:H i layer/p-type c-Ge substrate with double-side heterostructure, plotted as a function of annealing temperature.

Figure 4 shows the carrier lifetime of a-Si:H i layer/p-type c-Ge substrate with double-side heterostructure, plotted as a function of annealing temperature. The results were relatively correlated with the change of V_{OC} shown in Fig. 3. Therefore, the change of V_{OC} by post-annealing could be mainly explained by the passivation quality of a-Si:H for the c-Ge surface.

4. Conclusions

We fabricated a-Si:H/c-Ge heterojunction solar cells with a double heterostructure (DH), and investigated effects of post-annealing on characteristics of it. The improvement of the conversion efficiency compared to the solar cell having single heterostructure was obtained from the a-Si:H/c-Ge DH solar cell. We found the increase of V_{OC} at T_a > 150 °C and the optimum post-annealing temperature of 200 °C for the a-Si:H/c-Ge heterojunction solar cells. The results indicate that the a-Si:H double heterostructure is beneficial not only for c-Si-based heterojunction solar cells but also for c-Ge-based heterojunction solar cells.

Acknowledgements

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References

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