Extended Abstracts of the 2011 International Conference on Solid State Devices and Materials, Nagoya, 2011, pp1353-1354

Development of the TCO Layer for Nanocrystalline Cubic Silicon Carbide / Silicon Heterojunction Solar Cells with Aluminum Oxide Passivation Layers

Junpei Irikawa[1], Shinsuke Miyajima[1*], Tatsuro Watahiki[1] and Makoto Konagai[1,2]

[1] Tokyo Institute of Technology, S9-9, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8552, Japan
Phone: +81-3-5734-2662 E-mail: irikawa.j.aa@m.titech.ac.jp
[2] Photovoltaics Research Center, Tokyo Institute of Technology, 2-12-1, O-okayama, Meguro-ku, Tokyo, Japan

1. Introduction

For crystalline Si solar cells with thin wafers (100 μm or less), a heterojunction emitter is suitable because of the low process temperature and high passivation quality. Recently, n-type nanocrystalline cubic silicon carbide (nc-3C-SiC:H) was successfully developed as a n-type heterojunction emitter for p-type wafer.[1)] This material has two advantages. One is the high transparency in the blue light region due to the very low absorption coefficient.[2)] The other is the stability for moderate annealing temperature. The layer maintains a sufficiently low surface recombination velocity of 6 cm/s after annealing at 400 °C.

Up to now, we fabricated the nc-3C-SiC:H / c-Si heterojunction solar cell with a-$Al_{1-x}O_x$:H passivation layer.[3)] For the further improvement of the current density, the choice of a front transparent conductive oxide (TCO) is important. Since the deposition of the front TCO layer by sputtering causes the deterioration of passivation quality, the thermal annealing is required after the deposition of the front TCO to restore the sputtering damage. However, the annealing causes the change in the electrical properties of TCO. For example, the conventional Indium Tin oxide (ITO) layer has high carrier density after the thermal annealing.[4)] Then it causes a large decrease in short circuit current (J_{sc}) because of a significant free carrier absorption at long wavelength region (> ~1000 nm). On the other hand, the low carrier density and high mobility of In_2O_3:H after annealing were reported.[5)] Therefore, we combine the ITO and In_2O_3:H layer for front TCO layer. In this paper, we investigated the annealing properties of TCO for the heterojunction Si solar cell.

2. Experimental

The structure of the solar cell is Al / Ag / TCO / n-nc-3C-SiC:H / p-c-Si (without texturing)/ a-$Al_{1-x}O_x$:H / (point contact) Al. The wafer was p-type c-Si (CZ, 380 μm, (100), 2 Ωcm). After HF (2%, 1min) dip, the front nc-3C-SiC:H emitter (30 nm) was deposited by very high frequency (60MHz) plasma enhanced chemical vapor deposition (VHF-PECVD) technique. Detail deposition conditions of the nc-3C-SiC:H emitter were reported elsewhere.[1)] Subsequently HF (2%) dip was performed and Al_2O_3 films (30 nm) were deposited by atomic layer deposition (ALD) at a substrate temperature of 200 °C. Trimethylaluminum (TMA) and water (H_2O) were used as precursors of ALD. After Al_2O_3 deposition, the point contact opening was carried out by a reactive ion etching (RIE) with a hard mask. The opening area fraction of the hard mask was 5% with opening pitch of 2 mm. After the point contact opening, HF (0.5%) dip was performed again for a cleaning of the opened area. The aluminum (Al) electrode was deposited by thermal evaporation to the entire area of the rear surface. As front TCO layers, three different type of layers were considered: i) 60-nm ITO, ii) 60-nm In_2O_3:H and iii) 45-nm In_2O_3:H / 15-nm ITO stack. The ITO and In_2O_3:H layers were deposited by RF sputtering. The 60-nm ITO layer was deposited at a substrate temperature of 260 °C with Ar gas, the others were deposited at 150 °C with Ar+H_2 (1% H_2 in Ar) gas. Finally, the front Al (10 μm) / Ag (500 nm) grid was deposited on front TCO by thermal evaporation. Before characterization of solar cell, the annealing in forming gas (3% H_2 in N_2) was carried out.

*Present address: Institute of Physical Electronics, University of Stuttgart, Pfaffenwaldring 47, D-70569 Stuttgart, Germany

3. Results and discussions

Figure 1 shows the solar cell performances as a function of the annealing temperature. The open circuit voltage (V_{oc}) was improved by the thermal annealing at 300 °C. However, the thermal annealing at higher than 300 °C deteriorates the V_{oc}. It was reported that the optimum annealing temperature of the Al_2O_3 passivation layer deposited by thermal ALD was lower than 400°C.[6)] Therefore the difference in V_{oc} is due to the change in Al_2O_3 passivation quality.

The J_{sc} of the solar cells with In_2O_3:H and In_2O_3:H / ITO stack were much higher than that of the solar cell with ITO only. As mentioned above, the carrier density of ITO was increased by annealing. However, the carrier density in In_2O_3:H layer was decreased and the mobility was increased by annealing. Therefore, the free carrier absorption of In_2O_3:H layer is much smaller than that of ITO, resulting the higher J_{sc}. There is no significant difference between the J_{sc} of In_2O_3:H and In_2O_3:H / ITO stack. It indicates that the In_2O_3:H / ITO:H stack has sufficiently low carrier density with high mobility. Figure 2 shows the active area external quantum efficiency (EQE) of the solar cells annealed at 300 °C. If the TCO layer has high mobility and low carrier density, the refractive index and the extinction index of the layer are low. Therefore, the layer has low reflection on the surface and low free carrier absorption in the layer. From the slopes of the EQE at long wavelength region, we observed that the reflection on the surface (from 600 nm to 1000 nm) and free carrier absorption (from 950 to 1200 nm) of In_2O_3:H and In_2O_3:H / ITO stack are lower than those of ITO.

We also observe the obvious change in fill factor (*FF*) by annealing. As an overall trend, *FF* decrease with annealing at 350 °C or higher. This is mainly due to the decrease in the conductivity of nc-3C-SiC:H emitter and the increase in contact resistance between Ag and TCO. In addition, we observed the different annealing effect on each TCO. The samples with ITO and stacked In_2O_3:H / ITO shows the improvement in *FF* with annealing at 300 °C. This is due to the combination of the improvement of rear side contact and the good electrical properties of TCO itself. However, in case of In_2O_3:H, the annealing causes increase of the contact resistance between In_2O_3:H / nc-3C-SiC:H and/or Ag / In_2O_3:H. The increases of resistances have more impact on *FF* than the improvement of rear contact, causing the decrease of *FF* with the increase of annealing temperature. In addition, in case of In_2O_3:H / ITO stack, the annealing improved the contact resistance and maintained still good sheet resistance. Therefore, the *FF* of In_2O_3:H / ITO stack did not decrease so much by higher annealing temperature.

From these results, the solar cell with In_2O_3:H / ITO stack annealed at 300 °C showed a highest efficiency. The total area (1cm^2) efficiency of 17.2% (V_{oc} = 0.636 V, J_{sc} = 35.9 mA/cm^2, *FF* = 0.753) was achieved.

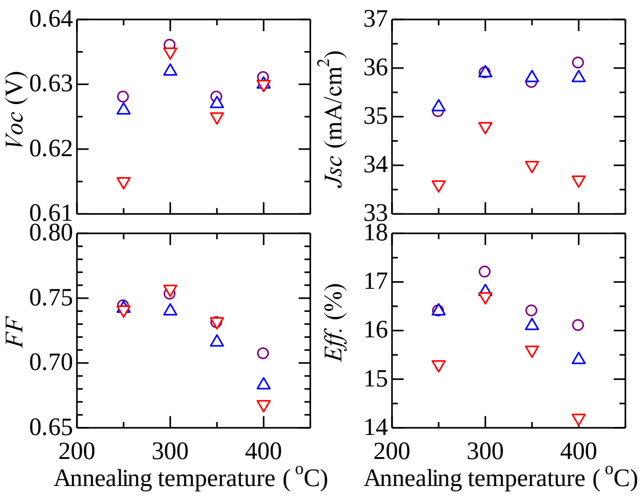

Fig.1 Dependence of solar cell parameters with ITO (inverted triangle), In_2O_3:H (triangle) and ITO:H/In_2O_3:H (circle) on annealing temperature.

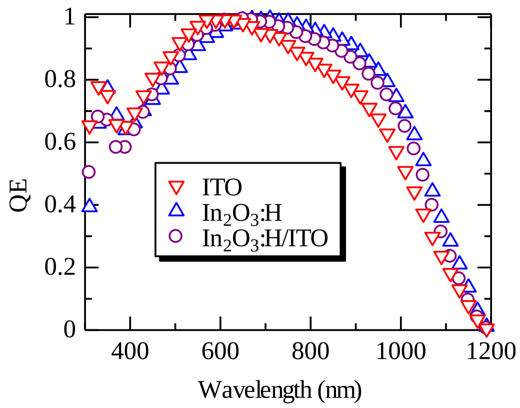

Fig.2 Active area EQE of the solar cells annealed at 300 °C. The effect of the electrode area with slight variation is eliminated.

4. Summary

ITO, In_2O_3:H and In_2O_3:H / ITO stack are developed as the front TCO layers for n-nc-3C-SiC:H / c-Si heterojunction solar cells with Al_2O_3 passivation layer. The solar cells with In_2O_3:H and In_2O_3:H / ITO stack show higher J_{sc} than that of the solar cell with ITO due to the low surface reflection and low free carrier absorption. The solar cell with In_2O_3:H / ITO stack shows higher fill factor than that of the solar cell with In_2O_3:H. The solar cell with In_2O_3:H / ITO stack shows an efficiency of 17.3% (V_{oc} = 0.636 V, J_{sc} = 35.9 mA/cm^2, *FF* = 0.753).

Acknowledgements

This work was partially supported by a Grant-in-aid for Scientific Research from the Japan Society for the Promotion of Science (JSPS) Fellows (No. 22-9476) and New Energy and Industrial Technology Development Organization (NEDO).

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