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a-Si Solar Cells Having More Than 9% Conversion Efficiency

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A systematic investigation has been made on both improvements of the film and junction qualities and an efficient utilization of the solar radiation in the long wavelength region in order to increase the conversion efficiency of a-Si solar cell. On the basis of these investigations, new cell structures and their fabrication technologies realizing more than 9 % conversion efficiency have been developed. A series of technical data on the cell fabrication and resulting photovoltaic characteristics are presented and discussed.

§1. Introduction

In a recent few years, a remarkable progress has been seen in both physics and technology of amorphous silicon (a-Si:H) as new electronic materials having the "structure sensitivity" [1]. In the field of solar cells, amorphous silicon possessing several remarkable advantages as a low cost solar cell material has been studied actively. The conversion efficiency of a-Si solar cell has been improved year by year through wide variety of tremendous R&D efforts [2], especially through the development of new amorphous silicon based alloys such as a-SiC, a-SiGe and μc-Si [3),4),5]. However, there essentially exist some limiting factor to be removed for attaining further high conversion efficiency. One of the limiting factors is the small mobility-lifetime products ascribed to the high-density of localized states, which restricted the practical dimension of an a-Si solar cell within 5000∿6000 A [6]. Because of a low absorption coefficient for the light wavelength region near or over the optical band gap energy (λ> 7000 A), lights of this region in the solar spectrum is not efficiently utilized for the photocarrier generation in a-Si solar cells of 5000∿6000 A. We have made a series of investigations to relieve these limitations from the various technological aspects. In this paper, new cell structure and thier fabrication technologies developed in the course of our investigation are presented.

§2. a-SiC/a-Si heterojunction solar cell

Recently it is found that the amount of boron in i layer affects its qualities [7]. Therefore, to improve the film and junction qualities, we have made a systematic investigation of plasma deposition system and have developed a horizontal separated three chamber system. With this system, we have fabricated a-SiC/a-Si/μc-Si heterojunction solar cell which are fabricated on the glass coated with transparent electrode (ITO/SnO_2). Variations of the built-in potential V_b, μτ products with the p layer thickness have been investigated. Here, all the cells have the same thickness of i and n layers, which are about 6000 and 500 A, respectively. Figures 1 (a) and (b) show the p layer thickness dependence of the built-in potential V_b [8] and μτ products [9], respectively. Built-in potential V_b is not so much different for these two systems, while μτ products is significantly different. We consider the reason of this difference being originated in boron and carbon atoms incorporated into i layer during the deposition. In case of single chamber system, the incorporation of boron atoms into i layer is thought to quantitatively proportional to the thickness of the p layer when we deposit p layer before i layer deposition, because boron atoms incorporated into i layer is supplied from

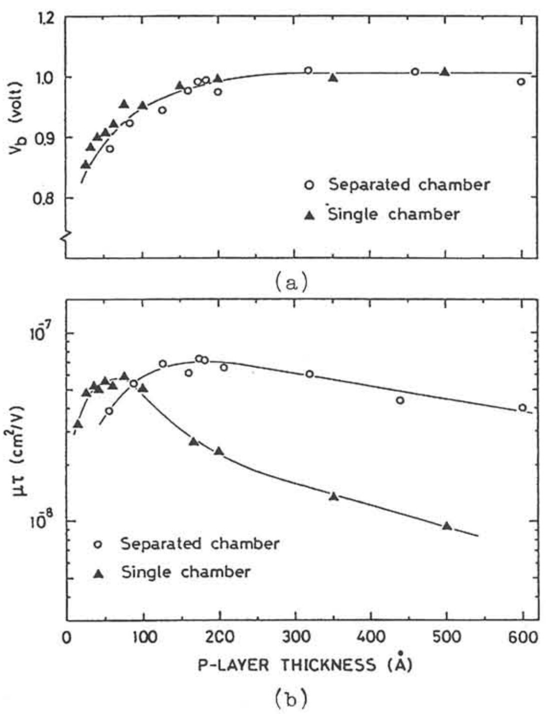

Fig. 1 The p layer thickness dependence of V_b and $\mu\tau$.

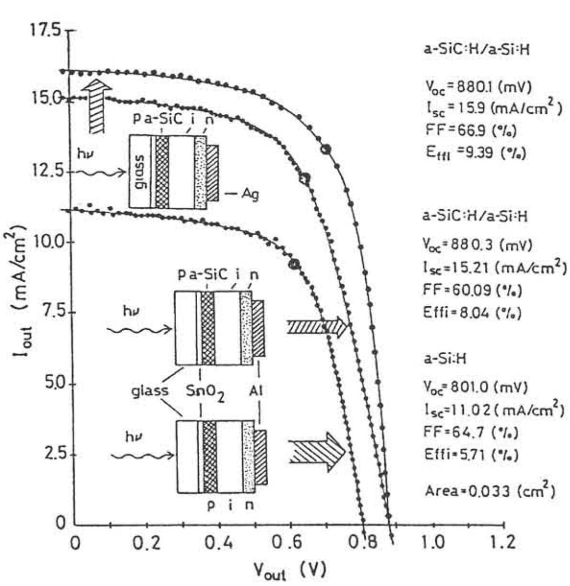

Fig. 2 I-V characteristics of a-SiC/ a-Si heterojunction solar cells.

the film which is adhered to the chamber wall and substrate holder. Therefore, the amount of boron atoms in i layer becomes larger with increasing the p layer thickness, and which varies the value of $\mu\tau$ products. While, such effect is reduced in the separated chamber system. The shift of the p layer thickness giving the maximum $\mu\tau$ products from 70 to 180 A in Fig. 1 (b) is explained by this effect. In the single chamber system, as reported in previous paper[3], the maximum conversion efficiency was obtained at the p layer thickness of 100 A and maximum $\mu\tau$ products is at 70 A. This discrepancy is understood by considering the increase of V_b in the p layer thickness from 0 to 200 A. While, in case of separated chamber system, the maximum point of $\mu\tau$ products agrees with maximum conversion efficiency point (180 A) because the maximum $\mu\tau$ products point is in the saturated V_b region.

In the course of optimization using this separated chamber system, we have obtained conversion efficiency of 9.39 % with V_{oc}=881 mV, I_{sc}=15.9 mA/cm^2 and F.F.=67.1 %, as shown in Fig. 2.

§3. inverted p-i-n solar cell

From the view of optics, recently, several trials for improving the conversion efficiency of a-Si solar cells have been made by means of the high reflective back electrodes[10] or textured back surface reflectors[11]etc. In spite of these efforts, no definite realistic technology has been developed so far. An attempt for saving the absorption losses of low energy photons near the band edge of a-Si has been conducted. It utilizes not only the high reflectance of the back electrode, but also the optical light confinement in a-Si layer caused by the diffuse reflectance on the back surface electrode. For this purpose, TiO_2/Ag/SUS substrate has developed. It has been confirmed from the S.E.M micrograph that there exist small grains having the size of several hundreds to submicron on the surface of this special substrate. Also, this substrate exhibits the reflectance composed of about 80∿90 % directional reflectance and especially 8∿18 % diffuse reflectance. The cells fabricated with this substrate bring about the enhancement of the collection efficiency in the longer wavelength region above 550 nm, as shown in Fig. 3, consequently produce 20 % higher short circuit current than that of the smoothly chemical

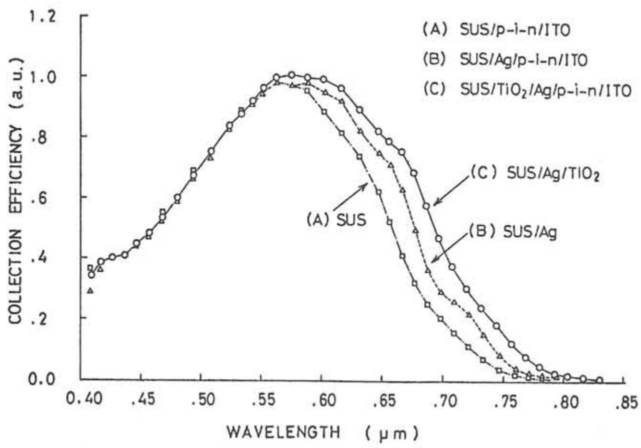

Fig. 3 Collection efficiency of inverted solar cells.

polished stainless steel substrate. This effect might be attributed to the absorption of low energy photons by the increase of the reflected light from high reflective back electrode and the increase of the optical pass length owing to the optical light confinement effect in a-Si layer. By using this high reflective semi-textured substrate, rather high conversion efficiency solar cell has been obtained so far. Cell structure is ITO/n-i-p a-Si/TiO_2/Ag/SUS inverted type. Typical performance is the conversion efficiency of 9.17 % with V_{oc}=881 mV, I_{sc}=16.14 mA/cm^2 and F.F.=64.5 %, as shown in Fig. 4.

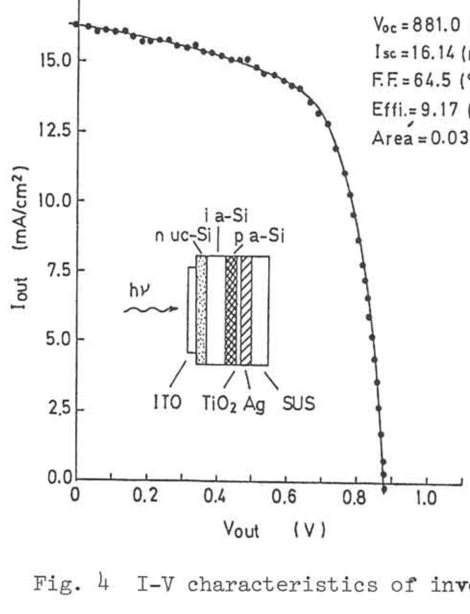

Fig. 4 I-V characteristics of inverted solar cell.

§4. a-Si/poly c-Si stacked solar cell

A deficiency of a-Si solar cells owing to the low absorption coefficient in the infrared region can be saved by combining it with materials having a narrow band gap, that is, a long wavelength light absorber. From this viewpoint, we have developed an a-Si/poly c-Si stacked solar cell. The concrete junction structure is ITO//n-i-p a-Si//n a-Si/poly c-Si//Al, as shown in Fig. 5. The polycrystalline silicon used were poly c-Si wafers (SILSO) prepared from casting of Wacker-Chemitronic (p type, 0.5∿10 Ω cm). a-Si layers were deposited on it succesively by GD method. This cell consists of two unit cells; a top n-i-p a-Si solar cell and a bottom a-Si/poly c-Si heterojunction solar cell, which are connected in optical and electrical series. The photovoltaic active layer of the top cell (i a-Si layer) has the bandgap of about 1.75 eV, while that of the bottom cell (poly c-Si) has the bandgap of about 1.1 eV. Therefore, the light in the long wavelength region which cannot be absorbed in the top cell can be utilized in the bottom cell.

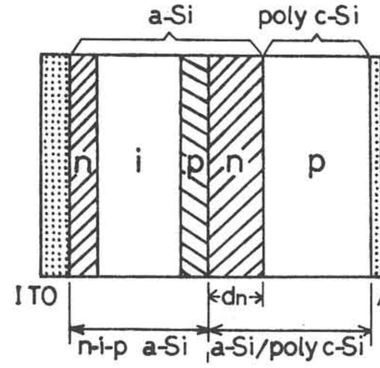

Fig. 5 a-Si/poly c-Si solar cell structure.

In this type cell, both the film qualities and thickness of all the a-Si layers composing the cell influence the photovoltaic characteristics. Systematic investigations on the optimization of a-Si layers have been performed. In the course of the investigations, it was found that the thickness of the n a-Si layer in the n a-Si/p poly c-Si bottom cell plays the most significant role on the photovoltaic characteristics. Figure 6 summarizes the cell performances as a function of the thickness of the n a-Si layer in the bottom heterojunction cell (d_n). Concerning the top n-i-p a-Si cell, we choose the neary optimized cell construction parameters, that is, the thickness of n, i and p layer in the top cell are chosen at 100, 5500 and 500 A, respectively. As be seen in this figure, the open circuit voltage V_{oc} increases rapidly from 0.5 V to 1.3 V at a threshold thickness of 3000 A, and the short circuit current I_{sc} decreases about 16 to 11 mA/cm^2. Because the value of V_{oc}, 1.3 V, corresponds to the summation of V_{oc} obtained in the a-Si top cell (0.8∿0.9 V) and that in the a-Si/poly c-Si bottom cell (0.45∿0.55 V), the stacked structure of both the unit cells is completed with the n a-Si layer thickness d_n more than 3000 A.

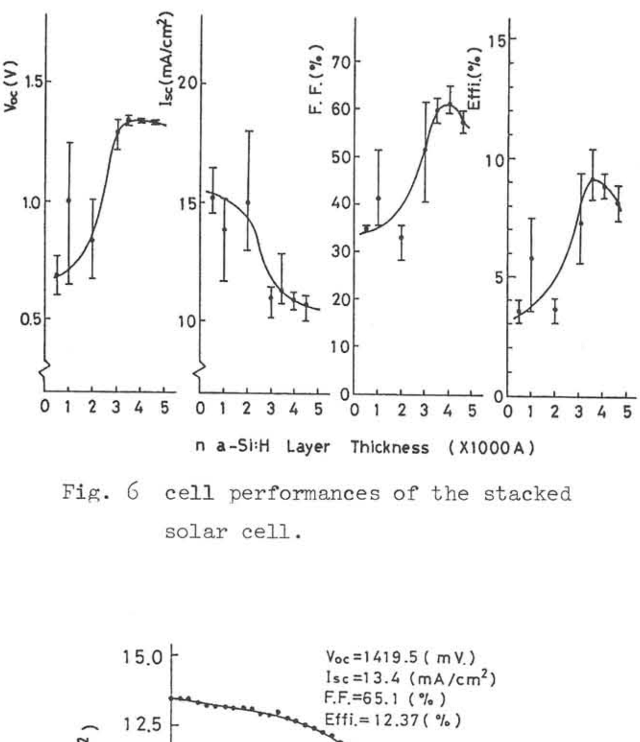

Fig. 6 cell performances of the stacked solar cell.

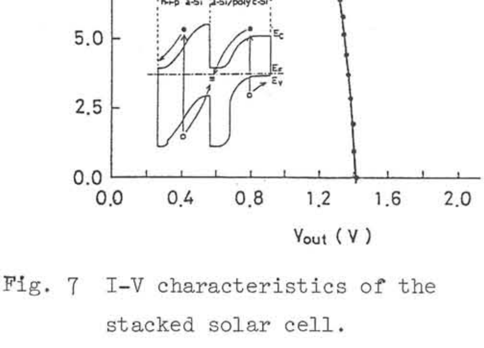

Fig. 7 I-V characteristics of the stacked solar cell.

At the present stage of the optimization, the conversion efficiency of more than 12 % with V_{oc}=1.4 V, I_{sc}=13.4 mA/cm^2 and F.F.=65 % is obtained under AM 1 illuminations, as shown in Fig. 7. The efficiency of this type cell seems to be limitted by the photocurrent yield in the a-Si top cell. Therefore, by adjusting the film quality of a-Si to this type of solar cell, a further high conversion efficiency can be expected to be obtained. Moreover, on this type cell, other polycrystalline materials (GaAs, Ge etc.) can also be used, and by using polycrystalline semiconductors prepared by thin-film-formation-techniques such as CVD, MOCVD and MBE, the cost reduction of solar cells may be still more promoted.

§5. Summary

In the course of some trials for the improvement of an a-Si solar cell efficiency, three types of new structure a-Si solar cell have been developed. Thier cell structure and fabrication technologies were presented and thier resulting effects were disscussed. All key technologes proposed here are practically available and mlght become real techniques for the fabrication of high efficiency a-Si solar cell.

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