MODELING OF TRIPLE JUNCTION A-SI SOLAR CELLS USING ASA: ANALYSIS OF DEVICE PERFORMANCE UNDER VARIOUS FAILURE SCENARIOS

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ABSTRACT

Triple junction a-Si solar cells have been modeled and simulated using the Advanced Semiconductor Analysis (ASA). The device performance is analyzed with numerically simulated I-V characteristics. We have studied several failure scenarios such as variations in the thickness of different layers of the multilayered triple-junction structure. Distinctive features of the I-V characteristics and solar parameters have been found which have been correlated with experimentally obtained results.

INTRODUCTION

Manufacturing activities of amorphous silicon (a-Si) based thin film solar cells have experienced a significant increase in the recent years. Solar panels with triple-junction spectrum-splitting structure are being manufactured in high-volume production. In the fabrication of an a-Si/a-SiGe/a-SiGe pin/pin/pin triple cell, the thickness, bandgap and other properties of each of the nine semiconductor layers as well as the other nonsemiconductor layers need to be accurately controlled in order for a triple cell to produce its highest power output. An unintentional change, or a "failure", of any one of these layers could lead to undesirable changes in the solar cell I-V characteristics and quantum efficiency. These changes are often abnormal and difficult to understand. Modeling of triple junction solar cells and numerical simulation of variation in layers to reproduce the effect of variations in the deposition sequence, could help to predict the changes in behavior of the solar cell performance. These predicted results would be extremely helpful to readily point out the failure mechanism by eliminating a large number of possibilities, should any of these failures occur in solar cell fabrication including PV manufacturing. Unfortunately, no reports of comprehensive study of failure analysis for the fabrication of multiplejunction solar cells and/or the comparison of these predicted results with real multi-junction devices have been found. To assist the optimization of solar cell fabrication and cost-effective industrial photovoltaic production, there is a strong need for the study of various possible failure scenarios in the deposition steps associated with the fabrication of multilayered thin film solar cells. In the present work, we selected a number of failure mechanisms that may occur during triple-cell device fabrication and studied the numerically simulated current-voltage (I-V) characteristics using Advanced Semiconductor Analysis (ASA), a program developed by Technical University of Delft [1]. Deviated solar cell I-V characteristics predicted under various failure scenarios are compared to that of a normal case. We cross examined and verified some of these predicted I-V performance with that of real triple-junction solar cell devices intentionally fabricated under these failure scenarios.

MODELING

A triple junction a-Si solar cell has been constructed in computer modeling with ASA. The cell has the following structure: Al/n-bottom/i-buffer/i-bottom/i-buffer/p-bottom/n-middle/i-middle/p-middle/n-top/i-top/p-top/TCO and the schematic diagram of this cell is given in Figure 1. This structure is taken as the standard for the present study and its simulated I-V characteristic is designated as the normal case. The other different cases chosen for the present study are shown in the Table 1. When any one layer is varied, all other layers have been kept unchanged in each of these scenarios.

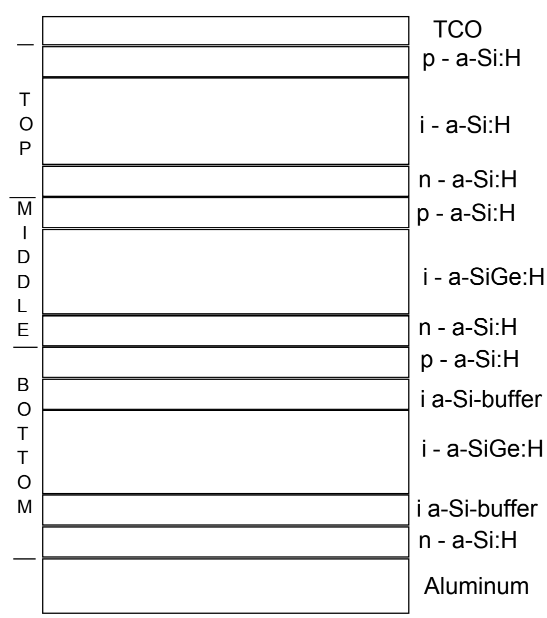

Fig. 1. Schematic diagram of the triple junction solar cell with various layers used for computer modeling by ASA.

The basic set of semiconductor equations represents a mathematical description of semiconductor device operation under non-equilibrium conditions. The basic semiconductor equations include the Poisson equation (eqn 1), the continuity equations for electrons (eqn 2) and holes (eqn 3) and the equations for electron (eqn 4) and hole (eqn 5) current densities. In the absence of magnetic field and for a uniform temperature in the device these equations have the following form:

$$div(\varepsilon\, grad\psi) = -\rho \quad \text{.................. (1)}$$

$$\frac{\partial n}{\partial t} = \frac{1}{q} divJ_n + G_{Opt} - R_{net} \quad \text{.................. (2)}$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q} divJ_p + G_{Opt} - R_{net} \quad \text{.................. (3)}$$

$$J_n = n\mu_n gradE_{FN} \quad \text{.................. (4)}$$

$$J_p = -p\mu_p gradE_{FP} \quad \text{.................. (5)}$$

In these equations ε is the permittivity of the semiconductor, ψ is the electrostatic potential with reference to the vacuum level E_0, ρ is the space charge density, J_n (J_p) is the electron (hole) current density, G_{opt} is the optical generation rate and R_{net} denotes the net recombination-generation rate of electrons and holes. n (p) is the free electron (hole) concentration, n (p) is the electron (hole) mobility, E_{FN} (E_{FP}) is the electron (hole) quasi-Fermi energy level and $\partial n/\partial t$ ($\partial p/\partial t$) is time rate change in the electron (hole) concentration.

EXPERIMENTAL

In the experimental part, triple junction solar cells have been deposited with standard parameters and whenever needed to skip/modify selected layers in the triple junction a-Si solar cell deposition process used by the University of Toledo. The I-V characteristics of the solar cells were measured under one sun intensity (AM1.5).

RESULTS AND DISCUSSIONS

As described in Table 1, various cases are computer modeled and I-V characteristics of corresponding structure with particular failure scenario have been simulated using ASA. The I-V characteristics of all the cases are shown in Fig 2 alongwith the normal standard case. A rough comparison of the cases depicted in Fig 2, reveals some characteristic features in the I-V curves arising out of the variation in thickness or absence of semiconductor layers in the standard triple cell deposition sequence. To take a close look at the failure case I-V curves, some of the curves are selected for analysis in Fig 3. We have chosen (i) the standard case, (ii) n-layer of the bottom cell deleted: case [E1], (iii) p-layer of the bottom cell deleted: case [D1] and (iv) n-layer of the middle cell deleted: case [B1] for our discussion in Fig 3. The first column in Fig 3 shows the simulated band energy diagram of the failure cases and the second column with the corresponding simulated I-V characteristics. Both the dark and illuminated I-V characteristics are plotted in the graphs. In case [E1] when the n-layer of the bottom cell is deleted, we obtain abnormal I-V curves for both dark and illuminated conditions. In the illuminated I-V curve, the change in the slope of the I-V curve at forward bias causes noticeable bending/deviation compared to standard one and could be treated as a fingerprint of this failure case. Comparing the solar parameters, V_{oc}, J_{sc} and FF decrease from their standard values. Also a noticeable deviation is obtained with dark I-V curve as seen from the simulation. When the p-layer of bottom cell is deleted (case [D1]) in the triple cell structure, simulated I-V curves also exhibit some special characteristics. In this case J_{sc} and FF decreases slightly, however V_{oc} drops to a lower value of 1.601 V. Also prominent change in the dark I-V curve has been observed. It seems that in dark, diode operation switches very slowly in forward bias for this case. The corresponding band diagram depicts how the p-i-n-p-i-n- -i-n structure deforms the shape of the standard band diagram. In case of n-layer of the middle cell deleted (case [B1]), one could find also a fingerprint characteristic in the I-V curve, the change in slope in the forward bias is quite different from that of the standard one and also that

Table 1: Description of different simulation cases for the triple junction solar cells studied in the present work

		Cases (In the parenthesis corresponding figure sub-numbers are given)	
n-layer	Top cell	No layer [A1]	Five times thickness [A2]
	Middle cell	No layer [B1]	Five times thickness [B2]
	Bottom cell	No layer [E1]	-
p-layer	Top cell	-	-
	Middle cell	No layer [C1]	Five times thickness [C2]
	Bottom cell	No layer [D1]	Five times thickness [D2]
i-layer	Top cell	-	Two times thickness [E2]
	Middle cell	-	-
	Bottom cell	Half thickness [F1]	Two times thickness [F2]

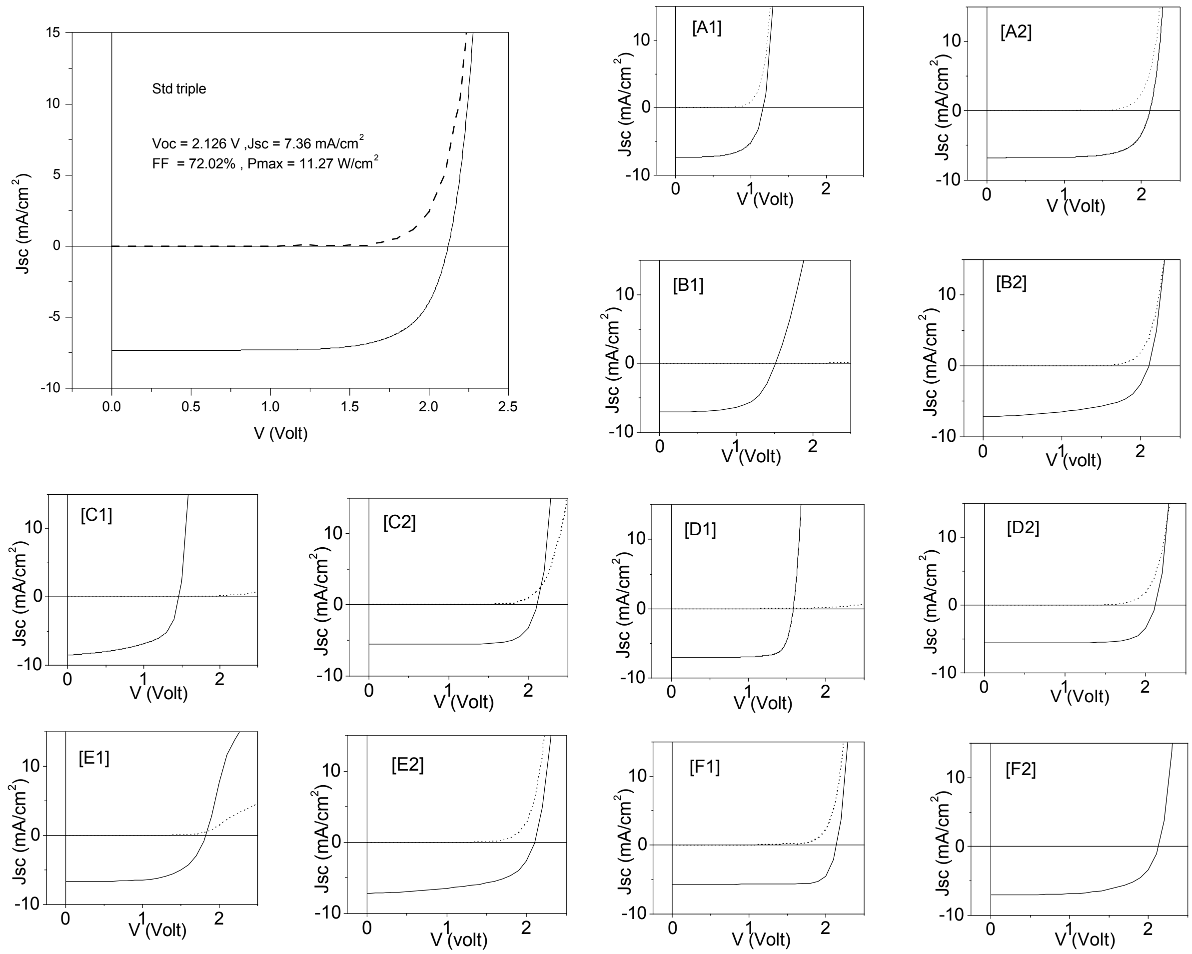

Fig. 2. ASA generated I-V characteristics of the standard triple junction solar cell and the selected failure cases designated in Table 1 as A1, A2, B1, B2, C1, C2, D1, D2, E1, E2, F1, and F2.

from the case [E1] where n-layer of the bottom cell was deleted or different from [D1] where p-layer of bottom cell was deleted. There are also characteristic changes in the solar cell parameters in this case [B1] compared to the standard values. Thus the shapes of the I-V curves both in illuminated and dark condition along with the solar cell parameters from simulation, produce “distinguishable” features for different failure scenarios as per our discussion of three of them and the standard one.

To verify the simulated I-V curves of the failure cases described in this paper, we cross-examined some of the cases and deposited triple junction solar cells with standard parameters used at the University of Toledo. To produce the “no layer” cases we skipped the selected layer in the deposition process and in the other cases varied the deposition time accordingly. In Fig. 3, we present three of the experimental cases, and compared them with already discussed simulated cases. The experimental standard case is in good agreement with the simulated one with respect to the shape and solar parameters. Now, in the case [E1], where n-layer of the bottom cell was deleted, we obtained the I-V characteristic of the experimental cell with the same fingerprint obtained from the simulation. The drastic change in the slope of the I-V curve at forward bias completely correlated with simulation results. The behavior of dark I-V curve is also similar to the prediction. In case of the p-layer of the bottom cell deleted (case [D1]) we also obtained good agreement between the experimental and simulated curves. However exact match is not obtained for all the solar parameters, while the trend in the shape of the I-V curves (both illuminated and dark) and change in solar parameter viz. drop in V_{oc} are similar in nature. We also correlated the case with n-layer in the middle cell deleted (case [B1]) and confirmed that experimental and simulated cases are well agreed. According to the experimental verification of the simulated cases, the I-V characteristics in Fig 1, obtained from the simulation could be used as fingerprint of the respective failure cases.

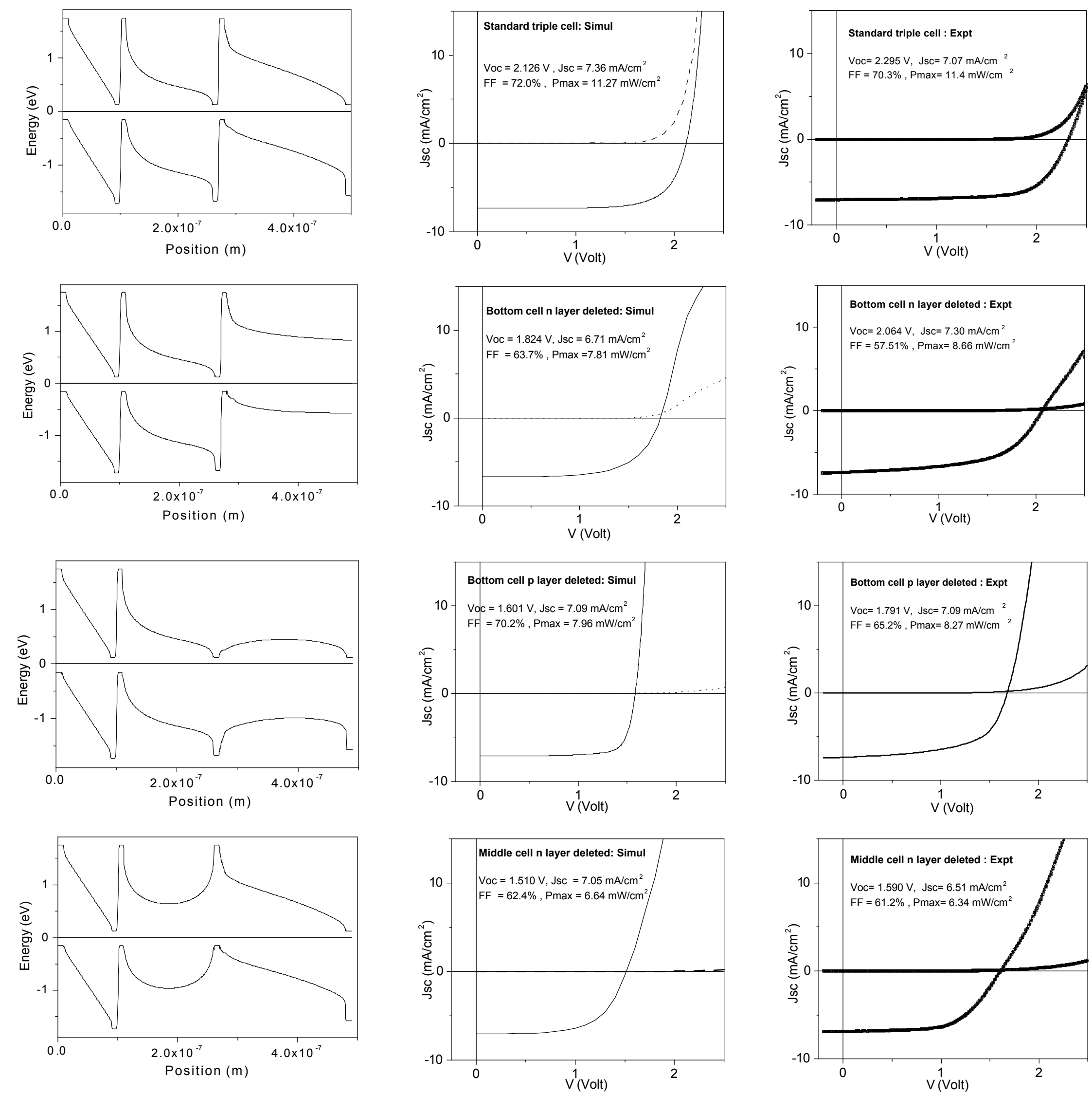

Fig. 3. ASA generated band-energy diagram (column 1), simulated I-V characteristics (column 2), experimental I-V characteristics (column 3) of the standard triple junction solar cell (row 1), case [E1] (row 2), case [D1] (row 3) and case [B1] (row 3) with corresponding solar parameters inset of each I-V graph.

CONCLUSIONS

Using ASA generated I-V results of a standard triple-junction a-Si/a-SiGe/a-SiGe solar cell and those under various “failure” conditions, we simulated the I-V characteristics when one of the layers is deposited away from the normal condition with respect to thickness. Various I-V performances are predicted under these failure scenarios which have distinguishable characteristics. Simulated I-V curves are correlated with that obtained by “real” experiments and good agreement has been confirmed. Therefore, the simulated I-V curves and analyses can be used to assist fabrication of triple-junction a-Si based solar cells in both research and manufacturing to quickly identify possible failure scenarios, should any of these occur.

ACKNOWLEDGEMENT

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REFERENCES

[1] R. E. I. Schropp and M. Zeman, “*Amorphous and Microcrystalline Silicon Solar Cells, Modeling, Materials and Device Technology”*, *Part II*, Kluwer Academic Publishers, 1998.