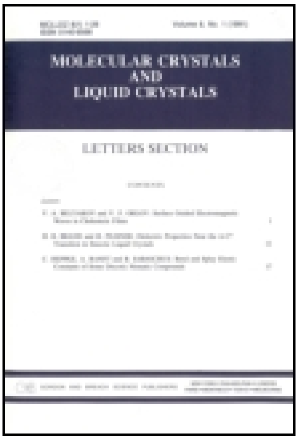

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Fabrication, and Characteristics of Pin-Type a-SiGe:H Thin-Film Solar Cells with a-Si:H Buffer and Graded Absorption Layer

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We have investigated the characteristics on hydrogenated amorphous silicon (a-Si:H) based solar cells of the various structures between the doped layers. Through basic experiments about p-i-n solar cells of different structures (i-a-Si:H layer, constant-gap i-a-SiGe:H layer, graded-gap i-a-SiGe:H layer and a-Si:H buffer layer at p/i interface), found that each cell has different advantages. Based on these results, we proposed the structure of a-Si:H buffer/graded absorption layer between the doped layers to improve the performance of hydrogenated amorphous silicon-germanium (a-SiGe:H) based p-i-n solar cell. The proposed structure has advantages to reduce the absorption losses for longer wavelengths and dopant penetration to i-layer. In the proposed structure, we achieved a higher open-circuit voltage (V_{oc}: 485 mV) and fill factor (FF: 0.57) than general a-SiGe:H solar cells.

Keywords a-Si:H; a-SiGe:H; a-Si:H buffer; graded a-SiGe:H; pin-type solar cell

Introduction

During the last three decades, hydrogenated amorphous silicon (a-Si:H) has been studied extensively as a basic material for thin film transistors (TFTs) [1], thin-film solar cells and many other applications. Also, hydrogenated amorphous silicon-germanium (a-SiGe:H) alloys were investigated as an optoelectronic material [2–6]. By alloying with germanium the band gap of a-SiGe:H can be varied from 1.1 eV (a-Ge:H) to 1.7 eV (a-Si:H) by changing the composition. A lower band gap increased the absorption to the solar spectra for longer wavelengths [7]. However, the material quality deteriorates as the optical band gap is reduced with an increase in germanium content. In a-SiGe:H based solar cells, the relatively poor electrical properties must be compensated by very thin i-layers and sophisticated cell designs. For example band gap gradings realized by gradually varying the germanium content in the i-layer regions adjacent to the p/i- and i/n- interface avoid band discontinuities and improve the hole transport [8–11]. Thus, significant improvement in solar cell performance were achieved by a band gap graded i layer [12–14].

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In this work, we have investigated the characteristics on hydrogenated amorphous silicon-germanium (a-SiGe:H) based solar cells of the various structures between the doped layers. However, the cells were faced with poor performance. Since the defect density of *a*-SiGe:H increases with decreasing optical band gap (i.e., increasing Ge content), one expects a high-defect density at the p/i and i/n interfaces, which will adversely affect the internal electric field and the carrier collection, resulting in poor open-circuit voltages V_{oc} and fill factors (FFs) [15]. To solve these problems, we proposed a-Si:H buffer/graded absorption layer structure to improve the performance of a-SiGe:H based p-i-n solar cell. The proposed structure has advantages to reduce the absorption losses for longer wavelengths and dopant penetration to i-layer. All films of amorphous materials were deposited by radical-assisted/plasma-enhanced chemical vapor deposition (RA/PECVD) method and the cell characteristics were measured by the solar simulator.

Experimental Details

Figure 1 shows each schematic of basic experiment in this study. We fabricated p-i-n solar cells with a simple structure of glass/ITO (Indium Tin Oxide)/p-a-Si:H (30 nm)/i-a-Si:H (200 nm)/n-a-Si:H (60 nm)/Al (200 nm). All films of amorphous materials were deposited by using 13.56 MHz radical-assisted/plasma-enhanced chemical vapor deposition (RA/PECVD) on ITO glass with sheet resistance 8 ohm/sq. The deposition conditions were: working pressure 750 mTorr, rf power 100 W for the dopant layer and 150 W for the intrinsic layer, substrate temperature 250°C. The SiH_4 gas was used as a gas source and the doping process was done by gas admixture of B_2H_6 and PH_3 for p-layer and n-layer respectively. The Al to deposit front electrode is used by the thermal evaporator. The cell characteristics were measured by an XEC-301S solar simulator under standard AM 1.5 G condition.

Results and Discussion

A. a-Si:H based p-i-n Solar Cells with Different Structures between the Doped Layers

In the first experiment, compared the characteristics of different structures cells with (a) a-Si:H p-i-n solar cell, (b) a-SiGe:H p-i-n solar cell (constant 80 sccm flow rate of

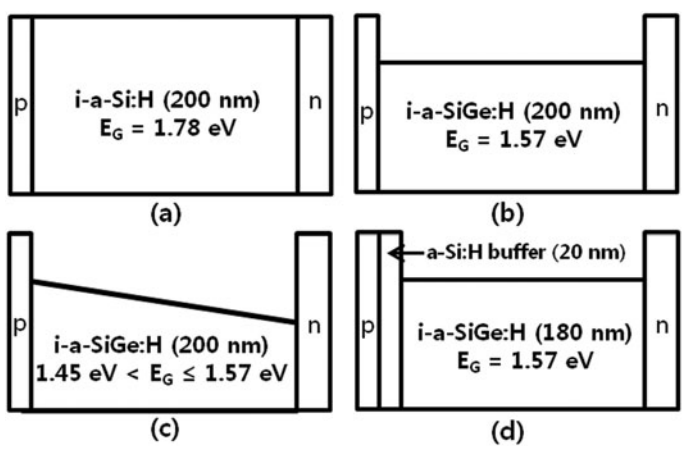

Figure 1. The schematic of p-i-n solar cells with (a) i-a-Si:H, (b) constant-gap i-a-SiGe:H, (c) graded-gap i-a-SiGe:H layer and (d) a-Si:H buffer/constant-gap i-a-SiGe:H.

Table 1. Electrical parameters of p-i-n solar cells with (a) i-a-Si:H, (b) constant-gap i-a-SiGe:H, (c) graded-gap i-a-SiGe:H and (d) a-Si:H buffer/constant-gap i-a-SiGe:H

Cell	V_{oc} (mV)	J_{sc} (mA/cm^2)	FF	Efficiency (%)
(a) i-a-Si:H	504	9.35	0.45	2.10
(b) constant-gap i-a-SiGe:H	414	17.82	0.48	3.50
(c) graded-gap i-a-SiGe:H	388	27.24	0.46	4.86
(d) a-Si:H buffer/constant-gap i-a-SiGe:H	509	20.44	0.40	4.07

GeH_4, $E_G = 1.57$ eV), (c) graded a-SiGe:H p-i-n solar cell (graded 80–140 sccm flow rate of GeH_4, 1.45 eV $< E_G \leq 1.57$ eV) and (d) a-SiGe:H p-i-n solar cell (constant 80 sccm flow rate of GeH_4) with a-Si:H buffer, respectively (Fig. 1). As compared with cell (a), the cell (b) had a higher J_{sc} and a lower V_{oc}. We confirmed that the conversion efficiency of the a-SiGe:H solar cell (Eff = 3.50%) was higher than a-Si:H solar cell (Eff = 2.10%). The reason is that the a-SiGe:H alloys had as an optoelectronic material with a lower bandgap than the a-Si:H, which allows an increase of the utilization of the solar spectrum at a long wavelength. From these results, indicate that the solar cell performance could be improved drastically. Figure 1(c) and Table 1(c) show the schematic of a-SiGe:H p-i-n solar cell with graded-gap i-a-SiGe:H layer and the highest J_{sc}. This cell structure was optimized to generate high current densities because it used a graded absorption layer. However, the p-i-n solar cells with a-SiGe:H alloy and graded-gap i-a-SiGe:H layer have the poor performance

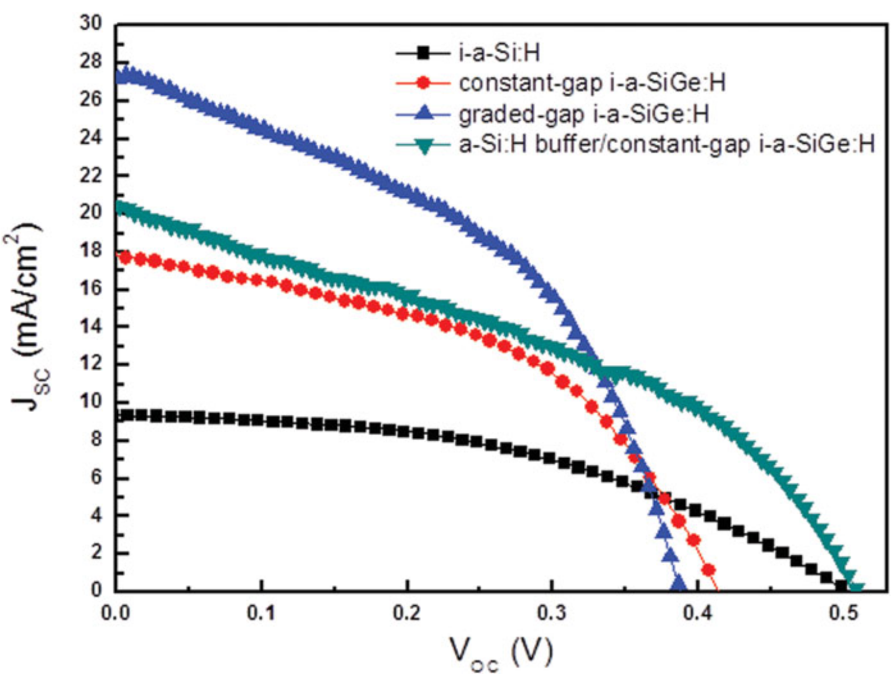

Figure 2. Photocurrent density-voltage (J-V) characteristics of p-i-n solar cells with (a) ■ i-a-Si:H, (b) • constant-gap i-a-SiGe:H, (c) ▲ graded-gap i-a-SiGe:H and (d) ▼ a-Si:H buffer/constant-gap i-a-SiGe:H layer.

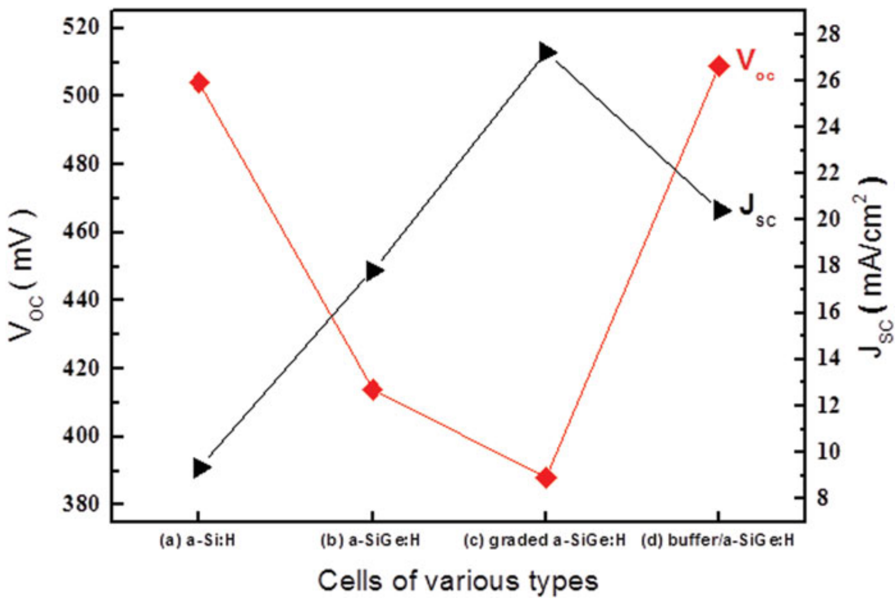

Figure 3. Comparison of open-circuit voltage (V_{OC}) and short-circuit current density (J_{SC}) with p-i-n solar cells of different structures.

(lower V_{oc}). The reason is that the solar cells have bandgap discontinuities and high-defect densities at the p/i and i/n interface, so we fabricated the a-SiGe:H p-i-n solar cell with a-Si:H buffer layer of thickness of 20 nm (Fig. 1(d)) to solve the lower V_{oc}. Compared to the bufferless (Fig. 1(b) and (c)), the a-SiGe:H p-i-n solar cell (Fig. 1(d)) with a-Si:H buffer layer considerably increases the V_{oc}. Consequently, it exhibits a improvement of conversion efficiency (Eff) than general a-SiGe:H p-i-n solar cell (Fig. 1(b)).

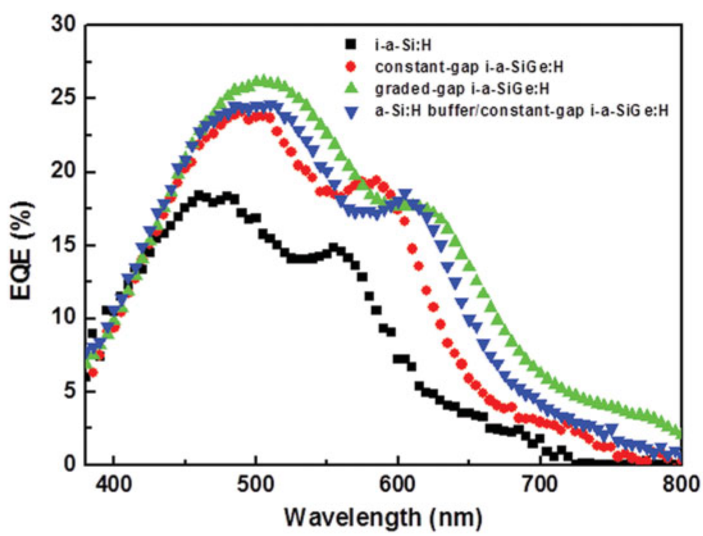

Figure 4. External quantum efficiency curve with p-i-n solar cells of different structures.

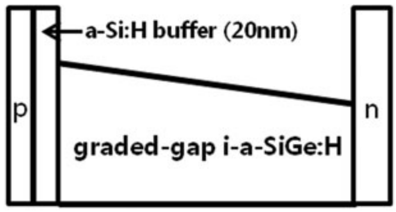

Figure 5. The schematic of a-SiGe:H p-i-n solar cell with a-Si:H buffer/graded-gap i-a-SiGe:H layer.

Figure 2 shows illuminated J-V curve of p-i-n solar cells with different structures between the doped layers. The values are summarized in Table 1. It is observed that the cell (c) of graded-gap i-a-SiGe:H has the highest J_{sc} of 27.24 mA/cm^2 and the cell (d) with a-Si:H buffer layer has the highest V_{oc} of 509 mV. Figure 3 shows the comparison of V_{oc} values and J_{sc} values in a-Si:H based p-i-n solar cells of different structures. From the fig. 3 and Table 1, it is shown that solar cell characteristics can be improved by using a graded absorption layer or a buffer layer at p/i interface.

Figure 4 shows the external quantum efficiency (EQE) as function of the wavelength for various pin-type a-Si:H based solar cells with differently prepared i-layer. The external quantum efficiency is defined as the ratio of collected charge carriers versus incoming photons at each wavelength. The figure 4 shows that the cell with a graded absorption layer has higher external quantum efficiency in the long wavelength region and a slightly lower response in the range of 580–600 nm.

B. a-SiGe:H p-i-n Solar Cell with a-Si:H buffer/graded-gap i- a-SiGe:H Layer

Based on the results of first experiments, confirmed that each cell has different advantages (a higher J_{SC} in graded a-SiGe:H p-i-n solar cell and a higher V_{oc} in a-SiGe:H p-i-n solar

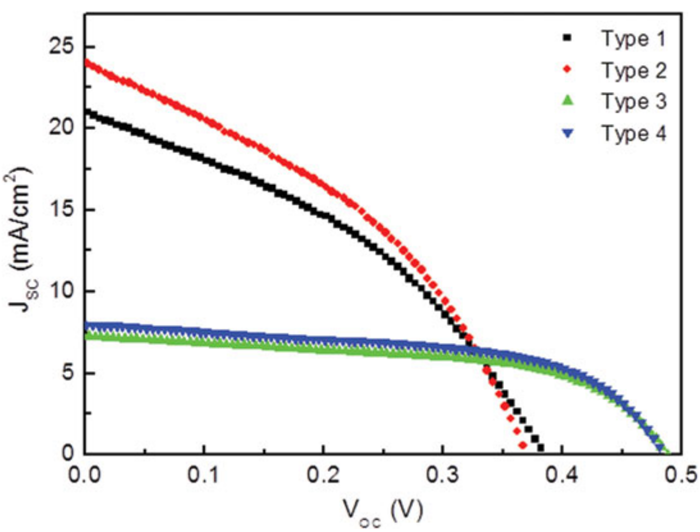

Figure 6. Photocurrent density-voltage (J-V) characteristics of a-SiGe:H p-i-n solar cells with a-Si:H buffer / graded a-SiGe:H layer in different conditions.

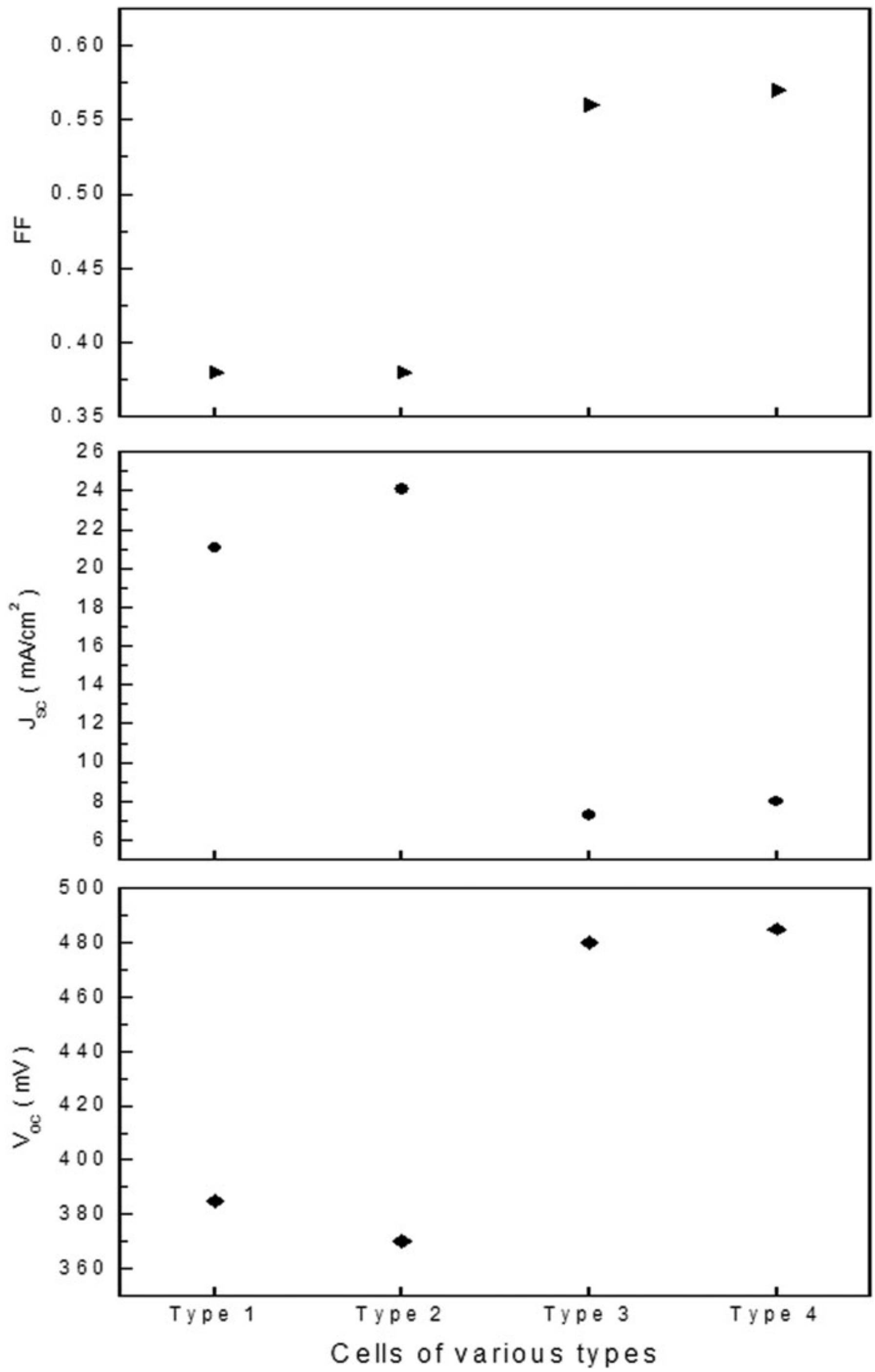

Figure 7. External parameters of a-SiGe:H solar cells with a-Si:H buffer / graded a-SiGe:H layer in different conditions.

Table 2. Electrical parameters of a-SiGe:H p-i-n solar cell with a-Si:H buffer/graded-gap i-a-SiGe:H layers

	Description	V_{oc} (mV)	J_{sc} (mA/cm^2)	FF
Group 1				
Type. 1	a-Si:H buffer (20 nm)/ graded-gap i-a-SiGe:H (200 nm, graded 70–130 sccm flow rate of GeH_4)	385	21.02	0.38
Type. 2	a-Si:H buffer (20 nm)/ graded-gap i-a-SiGe:H (200 nm, graded 80–140 sccm flow rate of GeH_4)	370	24.06	0.38
Group 2				
Type. 3	a-Si:H buffer (20 nm)/ graded-gap i-a-SiGe:H (180 nm, graded 70–130 sccm flow rate of GeH_4)	480	7.29	0.56
Type. 4	a-Si:H buffer (20 nm)/ graded-gap i-a-SiGe:H (180 nm, graded 80–140 sccm flow rate of GeH_4)	485	7.97	0.57

cell with a-Si:H buffer layer). Second experiment was progressed by motivating on the characteristics which showed before (in the first experiments). Figure 5 shows schematic of a-SiGe:H p-i-n solar cell with a-Si:H buffer / graded-gap i-a-SiGe:H layer. We compared a-SiGe:H solar cells (group 1) of a-Si:H buffer (20 nm) / graded i-a-SiGe:H layer (200 nm) with a-SiGe:H solar cells (group 2) of a-Si:H buffer (20 nm) / graded i-a-SiGe:H layer (180 nm) in several conditions. The J-V characteristics of the a-SiGe:H p-i-n solar cells with a-Si:H buffer / graded a-SiGe:H layer are shown in Fig. 6. Figure 7 shows the solar cell parameters of the proposed structures in several conditions. More detailed information about the cell performances can be found in Table 2. A group 1 of cells (Type. 1 and 2) had the higher J_{sc} than a group 2 of cells (Type. 3 and 4). By contrast, a group 2 of cells had the higher V_{oc} and FF than a group 1 of cells. In contrast to the expectation, a group 2 of cells had the poor the J_{sc}. We expect that the proposed structures (group 2) were not optimized to deliver high current densities because used the one which is thinner than previous a-SiGe:H absorber layer and also it is incomplete graded i-a-SiGe:H layer. Nevertheless, it has improved V_{oc} characteristic which 17% better than p-i-n solar cell of constant-gap i-a-SiGe:H layer (Fig. 1(b)) and also 25% better than p-i-n solar cell of graded-gap i-a-SiGe:H layer (Fig. 1(c)). and also FF is 0.57 which shows advanced characteristics. It is 18% better than p-i-n solar cell of constant-gap i-a-SiGe:H layer (Fig. 1(b)) and 23% better than p-i-n solar cell of graded-gap i-a-SiGe:H layer (Fig. 1(c)).

Conclusions

In this study, we have investigated the characteristics on a-SiGe:H based solar cells of the different structures (i-a-Si:H layer, constant-gap i-a-SiGe:H layer, graded-gap i-a-SiGe:H layer, a-Si:H buffer layer at p/i interface) between the doped layers. With the results from the experiment, we concluded that the a-SiGe:H based solar cell performance of poor V_{oc} can be improved by inserting buffer layer at p/i interface, and also the absorption losses for longer wavelengths can be reduced by graded absorption layer. Based on these results, we proposed the structure of a-Si:H buffer/graded absorption layer to improve the performance of a-SiGe:H based p-i-n solar cell. From the proposed structure, we expect to reduce the absorption losses for longer wavelengths and dopant penetration to i-layer. In particular, the V_{oc} and FF show a maximum for p-i-n solar cell with a-Si:H buffer (20 nm)/graded a-SiGe:H (180 nm, graded 80-140 sccm flow rate of GeH_4). The J_{sc} shows a maximum for p-i-n solar cell with a-Si:H buffer (20 nm)/graded a-SiGe:H (200 nm, graded 80–140 sccm flow rate of GeH_4). In this work, we haven't achieved improved all the electrical parameters (V_{oc}, Jsc and FF). However, we have shown a high potential for excellent performance of a-SiGe:H based solar cells in just a single junction device structure.

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