

HIGH EFFICIENCY AMORPHOUS SILICON GERMANIUM SOLAR CELLS

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ABSTRACT

We report high-efficiency single-junction a-SiGe n-i-p solar cells deposited using rf PECVD on stainless steel (SS) substrates coated with metal/ZnO back-reflector (BR). The initial and stabilized active-area efficiencies have been improved to 12.5-13.0% and 10.4%, respectively, for 0.25 cm² a-SiGe cells. The achievement of single-junction cells with such high efficiencies, equivalent to those for the state-of-the-art triple-junction solar cells, are important since this would lead to significant cost reduction in manufacturing. The key factors leading to these high efficiencies include the use of: 1) an optimized GeH₄ to Si₂H₆ ratio leading to a Ge content ideal for high-efficiency single-junction a-SiGe cell, 2) an optimized level of hydrogen dilution for the i-layer, and, most importantly, 3) a hybrid p-layer with the sub-layer near a-SiGe i-layer deposited at high temperature (140 °C) and the bulk of the p-layer deposited at low temperature (70 °C) for better transparency.

INTRODUCTION

Amorphous silicon germanium (a-SiGe) alloy has been widely used as narrow bandgap i-layers in multi-junction a-Si based solar cells [1, 2]. It is also noticed that as a single junction device, a-SiGe cell may reach a higher conversion efficiency than pure a-Si counterpart, if its a-SiGe i-layer possesses an appropriate Ge content and the fill factor keeps a good value. This paper reports our investigation on high efficiency single junction n-i-p a-SiGe solar cells, including the selection of the Ge content in a-SiGe i-layers with a high device quality and the interfacial matching between the the i-layer and p-layer.

EXPERIMENTAL

The single junction a-SiGe solar cell devices were deposited by rf PECVD on ZnO/Ag coated stainless steel substrate. It has the structure of SS/BR/a-Si n-layer/n-i buffer/a-SiGe absorber i-layer/i-p buffer/nc-Si p-layer/ ITO. The a-SiGe absorber i-layers were deposited using a gas mixture of disilane, germane and hydrogen with a varying germane to disilane ratio and a hydrogen dilution of 50-100. The illuminated I-V measurement was taken under a Xe lamp solar simulator. Quantum efficiency (QE) measurement was made in the range of 350–900 nm using a Xe lamp. Light soaking was done under 100mW/cm² light from a metal halide lamp for 1000 hours.

RESULTS AND DISCUSSION

Selection of Ge content in the a-SiGe i-layers

Fig. 1a, 1b and 1c show the V_{oc}, J_{sc} and conversion efficiency (EFF) of n-i-p a-SiGe solar cells as a function of the [GeH₄]/[Si₂H₆] ratio in the reaction gas, respectively. This set of n-i-p a-SiGe solar cells was deposited on SS without back-reflector. The solid lines in these figures are used only for guiding eyes. It is seen that with increasing GeH₄ fraction, J_{sc} increases, whereas V_{oc} decreases monotonically.

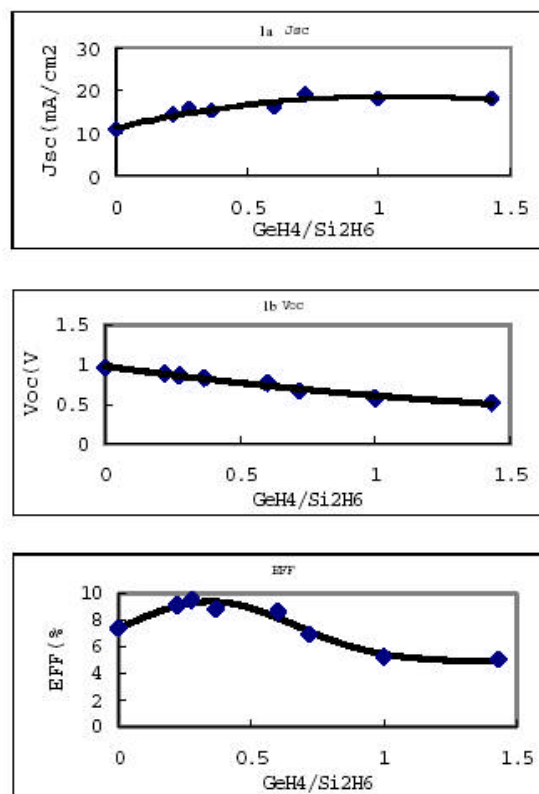


Fig. 1 Dependence of V_{oc} (1a), J_{sc} (1b) and EFF (1c) of n-i-p a-SiGe solar cells on GeH₄ fractions.

Under optimized deposition conditions, the fill factor (FF) for all this set of a-SiGe cells could be kept around 0.7, as a result the conversion efficiency of the n-i-p a-SiGe solar cells reaches a maximum at an intermediate $\text{GeH}_4/\text{Si}_2\text{H}_6$ ratio of about 0.3, before decreasing with further increasing $\text{GeH}_4/\text{Si}_2\text{H}_6$ ratio. This intermediate value of $\text{GeH}_4/\text{Si}_2\text{H}_6$ ratio is close to what we typically use for the i-layer in the middle cell of our standard triple-junction solar cells [3].

Interfacial matching between a-SiGe i-layer and p-layer

Interfacial matching between a-SiGe i-layer and p-layer plays an important role in determining the performances of n-i-p solar cells. It is found that an optimized p-layer ideal for wide bandgap a-Si top solar cell is not appropriate for intermediate bandgap a-SiGe solar cells.

Generally a-Si top cells with high performance ($V_{oc}=1.014\text{V}$ and $\text{FF}=74.6\%$) could be prepared using nanocrystalline silicon (nc-Si) p-layer deposited at a low substrate temperature ($T_s = 70^\circ\text{C}$), which consists of Si nanocrystallites embedded in a-Si networks and has a wide bandgap of about 1.9 eV [4]. But using this p-layer for the intermediate bandgap a-SiGe solar cells, the devices show not only the decay of FF, but also anomalous rollover behaviors of the illuminated I-V characteristics, as shown in Fig. 2a and 2b. It is further noted that there are two different rollover behaviors: one occurs at the voltage range close to V_{oc} (Fig. 2a), while the other larger than V_{oc} (Fig. 2b). In order to provide guidance for understanding these observations, we performed numerical simulations using AMPS Program developed at Penn State University [5], to evaluate scenarios leading to these unoptimized interface layers, and compared simulated results with our experimentally obtained results. Fig. 3a and 3b show the numerical modeling I-V characteristics, illustrating the two different rollover behaviors could be induced by the band-offsets and an extra wide bandgap interfacial layer between the i-layer and p-layer, respectively [6].

On the basis of above analyses, we performed experiments to decrease the bandgap of p-layer by deposition at a higher substrate temperature T_s (140°C). This narrow bandgap p-layer forms a good interface with the narrow bandgap (NBG) a-SiGe i-layer and leads to an ideal J-V characteristics, which is even better than that of top cells.

However the narrow bandgap p-layer, deposited at $T_s=140^\circ\text{C}$, is less transparent than p-layer deposited at $T_s=70^\circ\text{C}$, leading to a lower spectral response in the blue region. This kind of lowering of the external quantum efficiency in blue region is yet acceptable for middle and bottom cell in a triple stack. However, it is not acceptable for use in any single-junction solar cell. Therefore we tested a hybrid p-layer with the sub-layer near the narrow bandgap a-SiGe i-layer deposited at a high temperature (140°C) and the bulk of the p-layer deposited at 70°C for better transparency, as illustrated in Table 1.

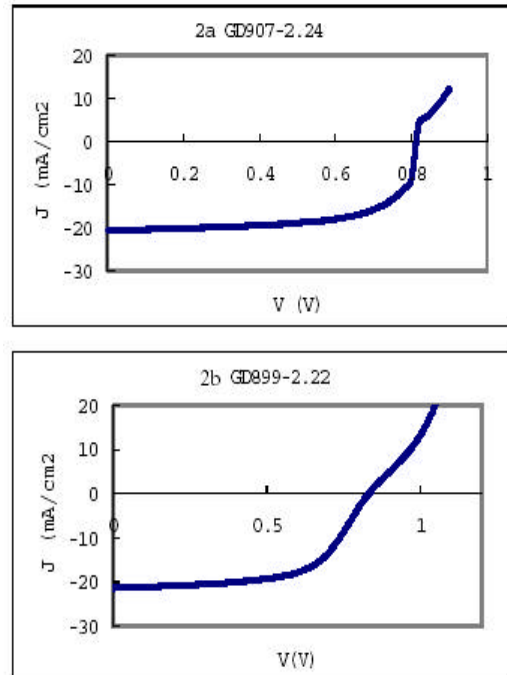


Fig. 2a and 2b Interfacial mismatch induced different rollover behavior in I-V curves.

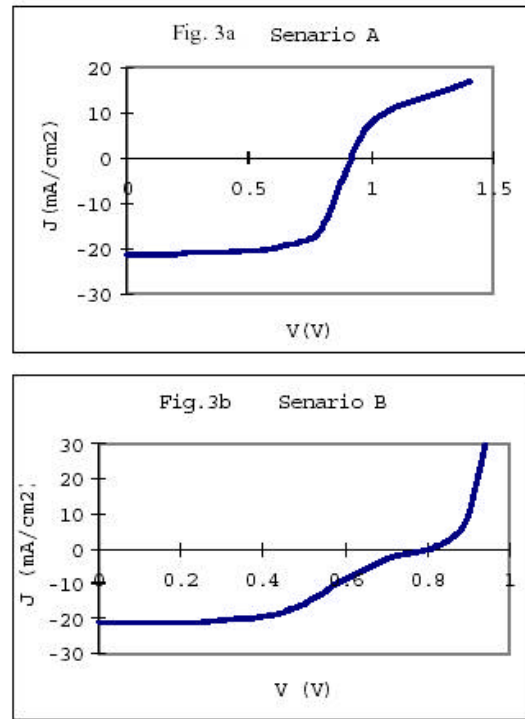


Fig. 3 Numerical modeling of different scenarios of the p-layer and p-i interface leading to poor I-V performance shown in Fig. 2a and 2b.

Table 1 a hybrid p-layer with sublayers deposited at Ts=140C and 70C.


<p>To have a p-layer that conforms good interface with a-SiGe and is more transparent, we used a hybrid, stacked p-layer with sublayers deposited at Ts=140 °C and 70 °C, respectively.</p>	 <p> p (Ts=70°C) p (Ts=140°C) i NBG a-SiGe n a-Si </p>
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Table 2 Average photovoltaic parameters of a-SiGe single junction solar cells

Sample	t ₁ (min)	t ₂ (min)	Voc (V)	Jsc (mA/cm ²)	FF (%)	η (%)
	Ts=140C	Ts=70C				
GD904	3	0	0.856	20.6	68.6	12.1
GD 907	0	3	0.856	20.7	65.9	11.7
GD 908	0.5	2	0.858	21	66.9	12.1
GD 919	1	2	0.847	21.5	70.1	12.8

Based on this approach we did a series a-SiGe solar cells, the obtained performances are much improved, as listed in Table 2. We used average value of 3 cells per run to evaluate the influence of p-layer on devices in consideration of the film uniformity. Among them the best I-V curve is illustrated in Fig. 4, with the photovoltaic parameters: $V_{oc} = 0.843V$, $J_{sc} = 21.32 \text{ mA/cm}^2$, $FF = 72.66\%$, and the initial active-area $\eta = 13.06\%$. Quantum efficiency measurement was also performed for this cell. After integrating the QE curves with AM1.5 spectrum, a current density of $\sim 19\text{mA/cm}^2$ was obtained.

After 3300 hours 1-sun light soaking, the stabilized efficiency is 10.4%. The achievement of single-junction cells with such high efficiencies, equivalent to those for the state-of-the-art triple-junction solar cells, are important since this would lead to significant cost reduction in manufacturing.

SUMMARY

We have prepared high-efficiency single-junction a-SiGe n-i-p solar cells deposited on SS coated with Ag/ZnO back-reflector. By using a hybrid nc-Si p-layer with the sub-layer near a-SiGe i-layer deposited at 140 °C and the bulk of the nc-Si p-layer deposited at 70 °C, the initial and stabilized active-area efficiencies have been improved to 12.5-13.0% and 10.4%, respectively, for 0.25 cm² a-SiGe cells. The achievement of single-junction cells with such high efficiencies, equivalent to those for the state-of-the-art triple-junction solar cells, are important since this would lead to significant cost reduction in manufacturing.

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FILENAME: gd919-2.24
 Voc = 0.843 V
 Jsc = 21.322 mA/cm²
 Contact area = 0.250 cm²
 FF = 72.662 %
 Pm = 13.060 mW/cm²

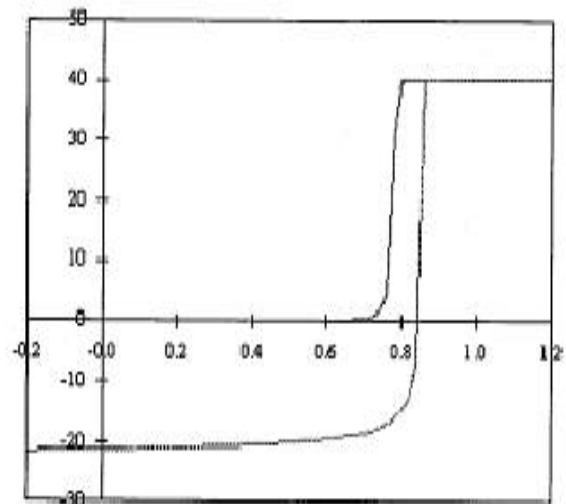


Fig. 4 I-V characteristics of a UT fabricated n-i-p a-SiGe cell, showing 13.0% initial, active-area efficiency.

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REFERENCES

[1] J. Yang, A. Banerjee, and S. Guha, Appl. Phys. Lett. 70 2975 (1997).

[2] P. Agarwal, H. Povolny, S. Han and X. Deng, "Study of a-SiGe:H Films and n-i-p Devices used in High Efficiency Triple Junction Solar Cells", J. of Non-Cryst. Solids, 2002, pp. 1213-1218.

[3] W. Wang, H. Povolny, W. Du, X.B. Liao and X. Deng, Triple-junction a-Si solar cells with heavily doped thin interface layer at the tunnel junction, IEEE-29, pp 1082-1085 (2002)

[4] Wenhui Du, Xianbo Liao, Xieshen Yang, Henry Povolny, Xianbi Xiang, Xunming Deng, Hydrogenated Nanocrystalline Silicon p-Layer in a-Si:H n-i-p Solar Cells, to be published.

[5] For AMPS, see <http://www.psu.edu/dept/AMPS/>.

[6] X. Liao, Z. Hu, Y. Xu, X. Zeng, H. Hao, H. Diao and X. Xiang Impacts of p-Type Interfaces on Performances of a-Si:H Based Solar Cells, PVSEC-14 Proceedings (2004)