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Improvement in the spectral response at long wavelength of a-SiGe:H solar cells by exponential band gap design of the i-layer

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Abstract

A new band gap profile (exponential profile) for the active layer of the a-SiGe:H single junction cell has been designed and experimentally demonstrated. In this paper we compare its optical and electrical characteristics with the two more common profiles: the U- and V-shapes. As predicted by the simulations, the new profile combines the advantages of both profiles. Like the V-shape, the exponential shape reduces the amount of Ge in the i-layer, decreasing both the space charge defect density inside the i-layer and the recombination losses. It also improves the electric field. At the same time, the exponential shape generates the same current density as the U-shape.

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1. Introduction

The optical characteristics of hydrogenated amorphous silicon–germanium alloys (a-SiGe:H) make them widely used as low band gap materials for multijunction solar cells. Alloying of a-Si:H with Ge reduces the band gap, permits the optical band gap to be tuned and the absorption coefficient to be increased at long wavelengths. Nevertheless, the electronic properties deteriorate with Ge alloying, increasing the midgap density of states, which influence the recombination rate and the field profile within the device. To overcome these limitations, the introduction of a band gap profile in the active layer of a-SiGe:H single junction cells has been studied. The profile of the intrinsic layer redistributes the space charge that produces screening of the electric field within the device. Thus, the profile determines the spatial electric field within the device and the collection of the photogenerated carriers. A profile structure helps to alter the recombination process and to improve the carrier collection in the i-layer.

Mainly two types of profiles have been investigated. The U-shape grading of the i-layer [1] leads to a better performance of the cell, by reducing the recombination at the p/i and i/n interfaces. The

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V-shape grading of the i-layer [2,3] reduces the trapped charge concentration and lowers the recombination losses by diminishing the average amount of Ge alloying.

Our experiments and simulations with red filtered light on single junction solar cells with an a-SiGe:H i-layer show an enhancement in the performance of the cell, especially in the open circuit voltage (V_{oc}) and the fill factor (FF) para- meters, using V-shape instead of U-shape. However, the current density (J_{sc}) decreases principally due to a reduction of the absorption in the long wavelength region. By computer simulation, we have found that these losses are mainly due to an average higher band gap. The loss of carriers by front or back diffusion also increases. To avoid these losses, we have designed a new profile for the interface region to yield the best performance under filtered light: the 'exponential shape' (E-shape) profile. The graded intrinsic layer is fabricated as a staircase profile. Taking short steps near the interfaces and elongating the steps away from the interfaces, the efficiency and the FF can be improved and an efficiency (η) higher than either the V-shape or the U-shape is achieved.

2. Experiment

The p–i–n a-SiGe:H solar cells studied in this research were grown in an ultrahigh vacuum multichamber system (PASTA) by plasma enhanced chemical vapour deposition (PECVD). The substrates were textured SnO_2 coated on glass (Asahi U-type). There was no ITO or ZnO at the back contact between the n-layer and the metal (Ag) for optical enhancement. Deposition was done at a substrate temperature of 200 °C, at a pressure of 1.65 Torr and an rf power density of 30 mW cm^{-2}. The structure of the devices included a graded a-SiGe:H layer separated from the doped layers by buffers made of a-Si:H. By varying the Ge content during deposition, the graded a-SiGe:H intrinsic layer is fabricated as a staircase profile of four steps between the buffer layers and the lowest band gap layer of 1.55 eV. The band gap of the films was obtained from the reflection and transmission optical measurements, identifying the band gap to the photon energy at which the absorption coefficient is $10^{3.5}$ cm^{-1}. Current–voltage (I/V) measurements of single a-SiGe:H cells were carried out in the dark, under AM 1.5 light and with filtered light. As a filter, a 100 nm a-Si:H layer on a glass substrate was used to simulate the light that reaches the bottom cell in a tandem structure.

3. Simulation model

Our simulations were made with the computer code D-AMPS. The electrical approaches of the Defect Pool Model (DPM) as proposed by Powell and Deane [4,5] were used to model the density of dangling bonds. The correlation energy U was assumed equal to 0.2 eV, the hydrogen concentration H to 5×10^{21} cm^{-3} and the freeze-in temperature was adopted equal to 500 K. From the three different microscopic chemical reactions proposed by Powell and Deane we selected the reaction where only one Si–H bond is broken and the hydrogen atom diffuses into the weak-bond site breaking the weak bond [6]; the spatial defect distribution that leads to a majority of positively charged defects ('D^h) near the p/i interface and a majority of negatively charged defects (D^e) near the i/n interface.

Since there is not yet a clear picture available for the distribution of the band offsets between the various layers in the structure we decided to split the band gap offset equally between the conduction and the valence band.

4. Results

4.1. U-shape vs V-shape: improved FF by lowering the Jsc

Fig. 1 shows a schematic band gap profile of the i-layer of the different a-SiGe:H single junction cells under study. Table 1 displays the experimental current–voltage (I/V) characteristics for the different band gap profiles. All the cells presented here have the same i-layer thickness, to limit the effects on the characteristics of the shape

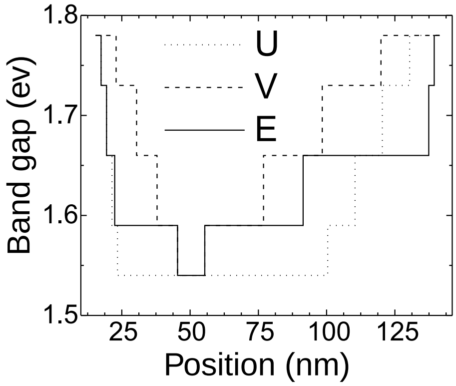

Fig. 1. Schematic i-layer band gap profiling of the 'U-shape', 'V-shape' and 'E-shape' structures, without buffer layers.

of the grading profile. The position of the minimum band gap in the V-profile was optimised by computer simulation [7].

Under filtered light and AM1.5 illumination, the V-shape leads to a significant improvement in V_{oc}, FF and efficiency (η), as compared to the U-shape. Our study (not shown here) revealed how both types of grading profiles contribute in a different way to the behaviour of the cell. On the one hand, the deeper front grading at the p/i interface in the V-type profile decreases the charged defect state density near the p/i interface due to the Fermi level dependence of the defect state distribution, as predicted by the defect pool model. This produces a reduction in the recombination process in this region, which in turn improves the V_{oc}. On the other hand, recombination in the depletion region (in the middle of the i-layer) can reduce the FF. The longer back grading reduces the density of charged defect states in the middle and near the i/n junction. The screening effect of the electric field is reduced, improving the mobility–lifetime–electric field ($\mu\tau E$) product and thereby improving the carrier extraction by decreasing the recombination in the bulk and in the rear part of the cell. The FF improves due to the reduction of the recombination. Together, both the front and the back grading of the V-profile lead to a better performance than the U-shape. Nevertheless, the V-shape suffers from a loss in the short circuit current, mainly due to an average higher band gap. The enhancement in carrier collection could not compensate the loss of carriers by the lower generation rate.

4.2. Exponential band gap profile

The E-shape has been designed to give the best performance under filtered light. The aim of the V-shape is to avoid defect states in the middle and rear parts of the i-layer in order to improve the electric field (carrier collection) inside the i-layer and to move the position of the minimum band gap away from the p/i junction. This has mainly improved the V_{oc} and the FF. The aim of the E-shape is to keep the above advantage of the V-shape, while enhancing the generation rate. For that, we have elongated the steps of the grading at deeper positions inside the i-layer (Fig. 1). This kind of grading profile increases the electric field in the bulk (reducing the charged defect states and the recombination losses) and generates more current due to an average lower band gap. Due to the length of the front grading of the proposed E-shape, the position of the minimum band gap moves away from the p/i junction, improving the V_{oc}.

Table 1
Solar cell experimental parameters of a U-, V- and E-shape p–i–n structure under illumination conditions of AM 1.5 spectrum without and with a filter of 100 nm thick a-Si:H

		V_{oc} (mV)	J_{sc} (mA/cm^2)	FF (%)	η
U-shape	AM 1.5	697	16.6	63.3	7.31
	Filtered	647	5.87	61.7	2.34
V-shape	AM 1.5	726	16.0	63.5	7.35
	Filtered	680	5.59	63.8	2.42
E-shape	AM 1.5	713	16.1	61.5	7.08
	Filtered	670	5.81	62.5	2.43

If we compare the profiles under filtered illumination the behaviour of the E-shape is comparable to the behaviour of the V-shape: better V_{oc} and η and slightly higher FF as compared to the U-shape. The new feature of the E-shape is the ability to maintain the improvements of the V-shape, while generating as much current as the U-shape, as shown by the J_{sc} (Table 1). In the V-shape, the use of a quite thick region of high band gap material near the p/i junction has the advantage that the V_{oc} and the electric field in the bulk of the i-layer are increased. This however reduces the electric field at the p/i junction affecting the collection of holes. On the other hand, the size of the band gap of the front grading generates less current. The front grading of the E-shape moves the position of the minimum band gap from the p/i junction (improving the V_{oc}), increases the electric field at the p/i junction (reducing the recombination losses) and generates more current (by shortening the length of the first steps of the grading).

In the E-shape, keeping the length of the back grading as in the V-shape, we shorten the length of the steps closer to the i/n junction to the minimum, elongating the steps with lower band gap. This results in a back region of higher band gap than in the U-shape, reduces the density of charged defect states and the screening effect on the electric field, improving the extraction of photogenerated carriers. At the same time, the back region with lower band gap than the V-shape enhances the current generation.

Combining both graded profiles, thinner at the p/i and i/n junctions and thicker in the middle and rear parts, the E-shape profile presents a general enhancement of the I/V characteristics (V_{oc}, FF and η) (Table 1) which is comparable with the V-shape profile, with the advantage of generating as much current as the U-shape.

5. Discussions

To decrease the density of charged defect states in the bulk of the i-layer, the V-shape replaces the low band gap (high defect density) material for a higher band gap (lower defect density) material. This is achieved by elongating the front and back grading at the expense of the minimum band gap layer. Fig. 2 shows the equilibrium distribution of positively charged (D^h) and negatively charged (D^e) defect states. The charged defect densities are significantly reduced by 30% within the i-layer with a V-shape, especially the dominant negatively charged defect (D^e) at the middle and rear parts of the i-layer. The electric field improves as a result of the lower screening by space charges; it becomes more uniform inside the i-layer and decreases at the p/i and i/n junctions (Fig. 3). The improvement of the electric field together with a lower defect density reduces the recombination (Fig. 4). This increases the $\mu\tau E$ product, permitting a better photogenerated carrier collection. However, the improvement in the photogenerated carrier collection, reflected in a higher FF than with the U-shape, does not compensate the losses in carrier generation within the i-layer, which accumulate to 8%.

With respect to the U-shape, the E-shape profile replaces the low band gap material for a higher band gap material in the middle and rear regions of the i-layer. The concentration of germanium in the film with the E-shape profile is 4% lower than that of a U-shape i-layer. The charged defect density, especially the dominant D^e at the middle

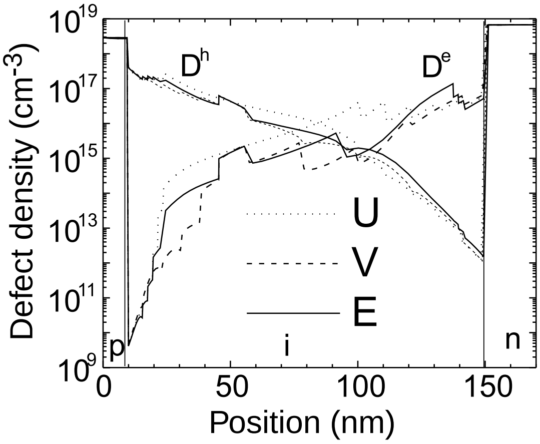

Fig. 2. Spatial distribution of positively charged (D^h) and negatively charged (D^e) defect states inside the i-layer with 'U-shape', 'V-shape' and 'E-shape' profiles at 0 V.

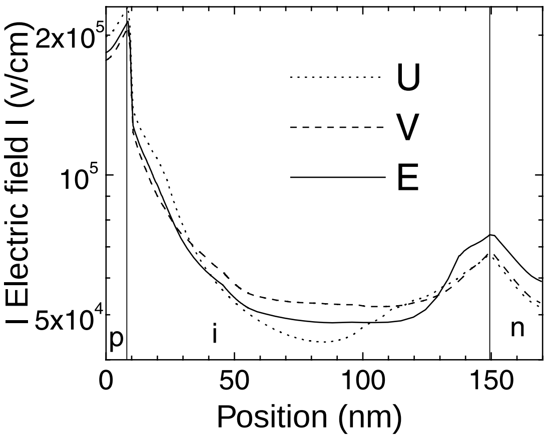

Fig. 3. Electric field within the 'U-shape', 'V-shape' and 'E-shape' structures at 0 V.

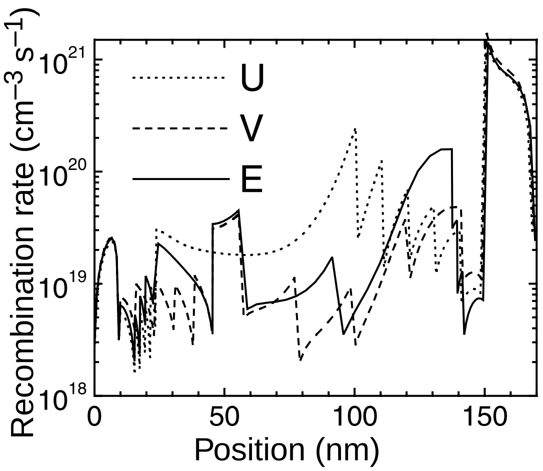

Fig. 4. Spatial recombination rate for the 'U-shape', 'V-shape' and 'E-shape' structures at 0 V.

and rear parts of the i-layer (Fig. 2), is significantly reduced by 12%. Due to the thin steps at the i/n junction, the material near this junction has a lower band gap than that in the U- and V-shape profiles. This results in a slight increase of the charged defect density near the i/n junction, which screens the electric field in this region (Fig. 3) and increases the recombination (Fig. 4). This disadvantage near the i/n junction is necessary to compensate the losses of photogenerated carriers in the middle of the i-layer. This does not prevent the decrease of the net recombination inside the i-layer by 16%. It also allows a carrier generation rate in the E-shape that differs from that in the generation rate of the U-shape by less than 0.5%.

6. Conclusion

We propose an exponential band gap grading (E-shape profile) of the i-layer of low band gap a-SiGe:H single junction solar cells that are to be used as a bottom solar cell in a tandem structure, with a distinct advantage in the spectral response at long wavelengths and with low recombination losses.

The E-shape combines the advantage of the U- and V-shapes. Like the V-shape, the E-shape reduces the amount of Ge in the material, reducing the space charged defect density inside the i-layer and thus reducing the recombination losses. It also improves the electric field. This is reflected by a high FF and V_{oc}. At the same time, the E-shape generates a current density as high as the U-shape. As a result, the E-shape leads to a better performance under filtered light than the U-shape.

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References

[1] E. Maruyama, Y. Hishikawa, A. Terakawa, K. Sayama, K. Ninomiya, Y. Hishikawa, H. Taurui, S. Tsuda, S. Nakano, Y. Kuwano, Mater. Res. Soc. Symp. Proc. 297 (1993) 821.

[2] S. Guha, J. Yang, A. Pawalikiewicz, T. Glatfelter, Appl. Phys. Lett. 54 (1989) 2330.

[3] J. Zimmer, H. Stiebig, H. Wagner, J. Appl. Phys. 84 (1998) 611.

[4] M.J. Powel, S.C. Deane, Phys. Rev. B 48 (1993) 10815.

[5] M.J. Powel, S.C. Deane, Phys. Rev. B 53 (1996) 10121.

[6] F.A. Rubinelli, R.E.I. Schropp, in: Proceedings of the 2nd W.C. PVSEC, Vienna, Austria, vol. 1, 1998, p. 998.

[7] F.A. Rubinelli, R. Jimenez Zambrano, J.K. Rath, R.E.I. Schropp, J. Appl. Phys. 19 (5) (2002), in press.