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STUDY OF BANDGAP PROFILING CONTROL ON PHOTOVOLTAIC PERFORMANCE IN THE THREE STACKED AMORPHOUS SOLAR CELLS

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ABSTRACT

A series of systematic experiments has been made on a bandgap profiling control using a-SiGe and a-SiC cells to clarify the cause for the improvement of the photovoltaic performance by the bandgap profiling in the photovoltaic active layer. It has been shown from the analysis that the most important contribution to the cell performance is an optimization of the ambipolar carrier collection by the bandgap profiling. On the basis of the results, an efficiency of 10.1% was obtained at the promising a-SiC/a-Si/a-SiGe multi-bandgap stacked cell by the bandgap profiling.

INTRODUCTION

We have made a study of the stacked amorphous solar cell and achieved an initial efficiency of 10.0 % with a projected degradation ratio of 10%/year by a-Si/a-Si/a-SiGe stacked cell [1],[2]. For practical application, it is important to improve the initial efficiency and stability. Multi-bandgap stacked solar cells are the promising technology for improved performance. We are developing an a-SiC/a-Si/a-SiGe multi-bandgap stacked cell [1]. If the quality of amorphous silicon alloys are improved, the multi-bandgap stacked cells will achieve a higher efficiency than conventional stacked cells.

As another approach, it has been reported that the performance of a-SiGe cells can be improved by the bandgap profiling in the photovaltaic active layer [3],[4],[5]. According to these results of the computer simulation, the improvement is caused by the increase of the electric field for holes within the cell. But the physical mechanism has not yet been clarified. Therefore, in order to clarify the physical mechanism by the experimental approach, we have made a series of systematic experiments on the bandgap profiling. And on the basis of the analytical results, we researched the multi-bandgap stacked cells with bandgap profiling in order to optimize the cell design.

EXPERIMENTAL

ITO/pi(a-SiGe)n/stainless steel (S.S.) cells having i layers with saddle shaped graded bandgap profiles were prepared for measurements of I-V characteristics and light-induced degradation performances by a chemical vapor deposition.

And ITO/pi(a-SiGe)n/ITO and ITO/pi(a-SiC)n/ITO cells were prepared for analysis and a-SiC/a-Si/a-SiGe multi-bandgap stacked cell were also prepared.

RESULTS AND DISCUSSION

Performances of a-Si alloy materials

a-SiGe:H, a-Si:H and a-SiC:H were used to control the bandgap. These materials were deposited under high hydrogen dilution conditions to obtain the high quality by a chemical vapor deposition [6]. The dark and photoconductivity of these amorphous alloys are shown in Fig.1. The amorphous alloys which have photoconductivity more than 10^{-5} $(\Omega \cdot cm)^{-1}$ were obtained for a range of optical bandgap from 1.39 eV to 2.0 eV.

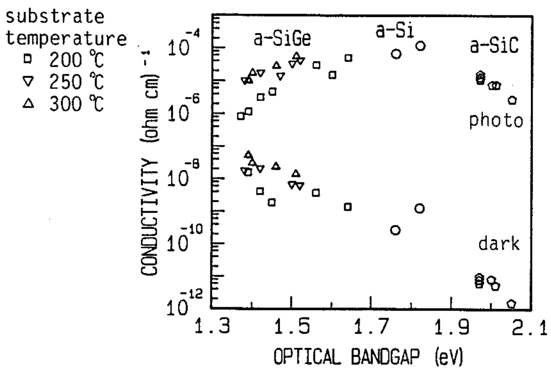

Fig.1 Dark and photoconductivity of a-SiGe:H,a-Si:H and a-SiC:H films versus optical bandgap

Composition profile

The bandgap profiles were controlled by source gas mixing ratios. So, a composition profile was analyzed by the Auger electron spectroscopy (AES). The film thickness was 2500 A and the optical bandgap was changed from 1.45 eV to 1.75 eV. The Si and Ge composition can be controlled smoothly as shown in Fig.2.

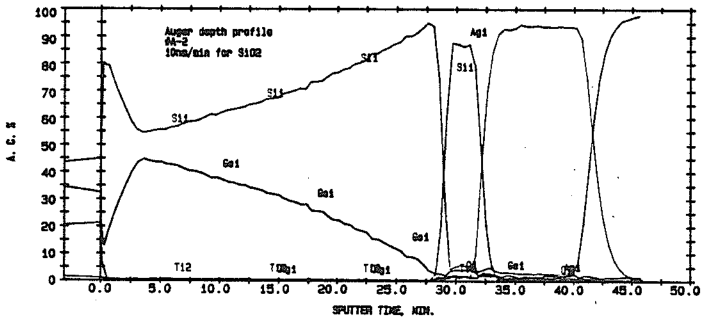

Fig.2 Si and Ge composition profile by Auger electron spectroscopy

Performances of a-SiGe

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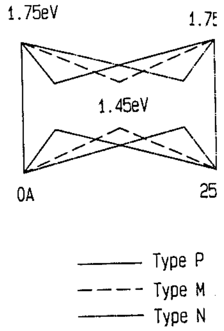

Fig.3 Bandgap profi
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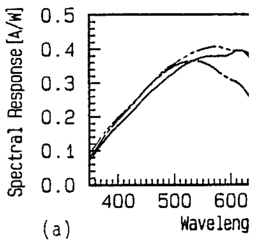

Fig.5 Spectral respons
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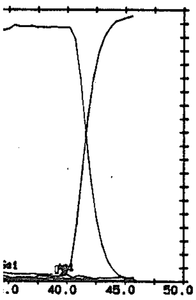

electron spectroscopy

Performances of a-SiGe cells with bandgap profiling

The performances of the a-SiGe cells with bandgap profiling as shown in Fig. 3 (Type P, M, N) were measured under AM1, 100 mW/cm^2 light and red light (AM1, 100 mW/cm light through a red (>660 nm) cut-on filter). The performances are shown in Fig.4 (a),(b) including performances of a-SiGe cell with 1.52 eV constant bandgap. The short circuit current, F.F. and output power increase as the position of the minimum bandgap changes from the n layer side to the p layer side. These performances of Type P cell are improved compared with those of the constant bandgap cell.

To analyze the performances, the ordinary spectral responses and the spectral responses under bias voltage of 0.3 V normalized by that under bias voltage of 0 V were measured and are shown in Fig.5 (a),(b). The spectral response and the bias voltage dependence of Type P cell are improved at the long wavelength.

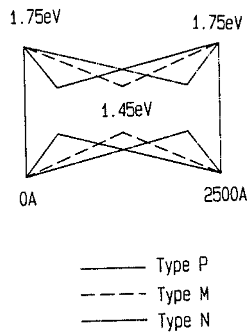

Fig.3 Bandgap profiles of a-SiGe cells (Type P, M, N).

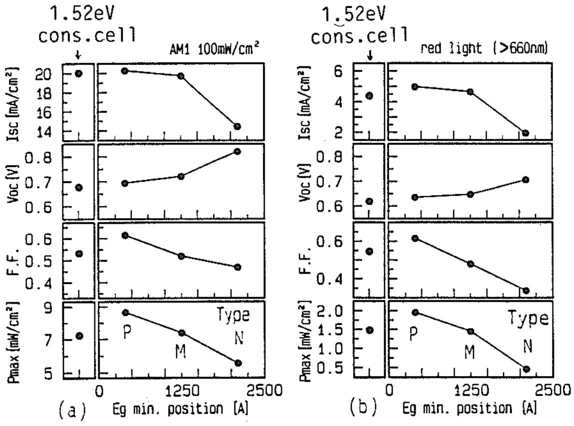

Fig.4 Cell performances of a-SiGe cells (Type P,M,N and 1.52eV constant bandgap cell) under AM1,100mW/cm^2 light (a) and red light (b).

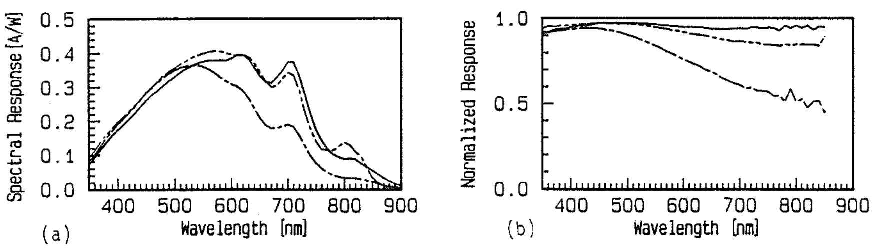

Fig.5 Spectral responses (a) and normalized spectral responses (b) of a-SiGe Type P (———), Type N (—·—) and 1.52eV constant bandgap cell (—··—).

Light-induced degradation of a-SiGe cells with bandgap profiling

The light-induced degradation performances of the a-SiGe cells (Type P, N and 1.52eV constant bandgap cell) which were exposed to AM1.5, 10 SUNS light were measured under the red light (AM1, 100mW/cm^2 light through a red (>660nm)cut-on filter). The cells kept on open circuit condition during the exposure. The original performances and the normalized performances by the initial values are shown in Fig.6(a),(b). The initial output power of the Type P cell is larger than that of the other cells. And the degradation ratio of the Type P cell is smaller than that of the other cells.

The bandgap profiling is useful to obtain a more efficient and more stable cell than the conventional cell.

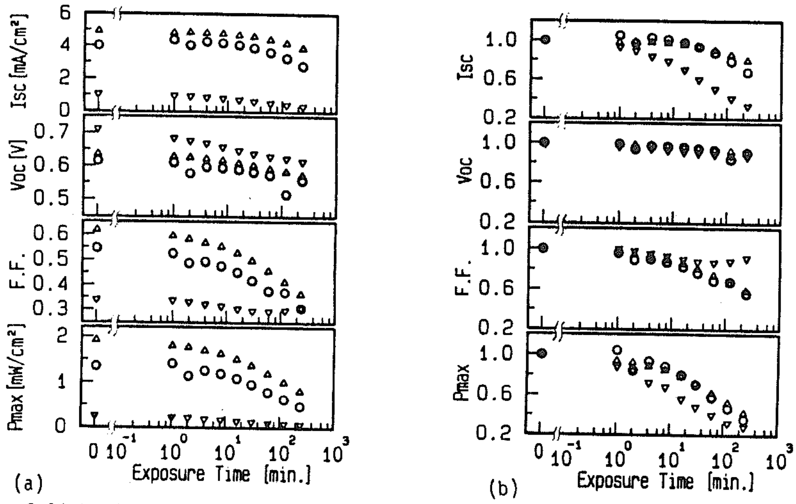

Fig.6 light-induced degradation performances under red light of a-SiGe Type P (△),Type N(▽) and 1.52 eV constant bandgap cell (O) which is exposed to AM1.5, 10 SUNS light [Original (a) and normalized (b) data].

Carrier transport

The performances of a-SiGe cells can be improved by the bandgap profiling as mentioned above. In order to clarify the physical mechanism by the experimental approach, we have made a series of systematic experiments.

To evaluate the effect of the bandgap profiling on the carrier transport, four type cells were prepared. The cells have the transparent electrodes at the both sides and have a p/i interface layer which have larger optical bandgap than that of the i layer as same as conventional cell, as shown in Fig.7. The i layers were made of a-SiGe and a-SiC. The bandgap profiles of these cells are shown in Fig.8 (a-SiGe Type P,N and a-SiC Type P,N).

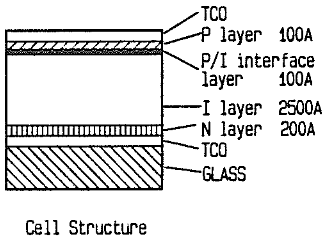

Fig.7 a-SiGe and a-SiC cell structure for the analysis.

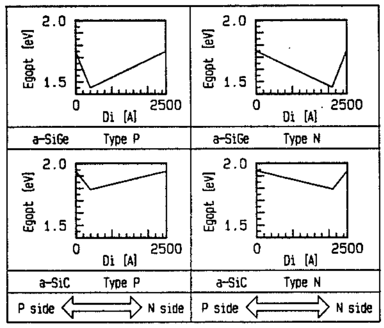

Fig.8 Bandgap profiles of a-SiGe cells (Type P,N) and a-SiC cells (Type P,N).

By the time-of-flight technique using a dye laser with 470 nm light, the charge collections of the a-SiGe Type P and N cells as a function of the externally applied voltage were measured. The light was entered from the p layer side to measure the electron collection and it was entered from the n layer side to measure the hole collection. The experimental data are shown in Fig.9(a),(b). At the same applied voltage, the electron collection of Type P cell is smaller than that of Type N cell, but the hole collection of Type P cell is larger. These experimental data suggest a possibility that the electron transport is reduced but the hole transport is improved in the Type P cell by the bandgap profiling.

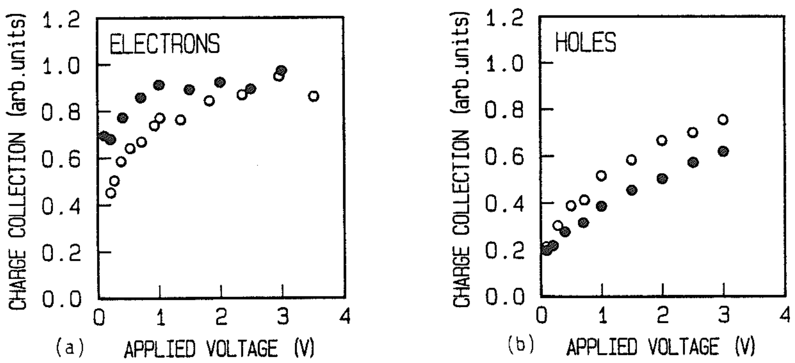

Fig.9 Electron collection (a) and hole collection (b) of a-SiGe Type P (○) and a-SiGe Type N (●) cell.

The hole and electron transports were evaluated under a steady light like a operating condition. The blue light (AM1, 100mW/cm light through a blue (<420nm) cut-on filter) was irradiated to the a-SiGe Type P,N and a-SiC Type P,N cells from the n layer side. Under this condition, carriers were generated near the n layer side and electrons were collected to the n layer immediately but holes were transported to the p layer through the i layer. The hole transport can be evaluated by the bias voltage dependence of a output current, in other words it can be evaluated by the F.F. of the cell performance under blue light from the n layer side. In the same manner as these experiments, the electron transport can be evaluated by the F.F. under blue light from the p layer side. The cell performances under blue light from the n layer side and tne p layer side are shown in Table I and Table II. In the a-SiGe cells, the F.F. of the Type P cell is larger than that of the Type N cell under blue light from the n layer, but the F.F. is almost same under blue light from the p layer. These results suggest that hole transport is improved but electron transport is not improved in the Type P cell and agree with the results of the time-of-flight measurement. But, in the a-SiC cells, the F.F. of the Type P cell is smaller than that of the Type N cell under blue light from the n layer side contrary to the experimental result of the a-SiGe cell. This result suggests that hole transport get worse in the a-SiC Type P cell.

The cause for the change of the hole transport by the bandgap profiling was investigated. It can be considerd that the electric field for holes within the cell is increased in the a-SiGe cell. But, in the a-SiC cell, if the increase of the electric field within the cell was a more effective cause to improve the cell performances, the F.F. of the Type P cell would be larger than that of the Type N cell. But the experimental results are contrary and can not be explained only by the increase of the electric field within the cell. In comparing the a-SiGe Type P cell with the a-SiC Type P cell, it can be considered that the bandgap profiling produces an almost equivalent increase in the electric field within the cell. But the mobility*lifetime ($\mu\tau$) products of holes and electrons near the n layer of a-SiGe Type P cell are larger than that of the a-SiC Type P cell , because the region of a-SiGe cell contain a few germanium like a-Si and that of a-SiC cell contain many carbon. Therefore, in the a-SiGe Type P cell which has a larger $\mu\tau$ product of holes near the n layer, the transport of holes which is genarated near the n layer is improved, even if the electric field near the n layer is small. But the $\mu\tau$ product of holes near the n layer of a-SiC Type P cell is small , and the hole transport is worse. With these idea about the increase of the electric field for holes within the cell and the distribution of $\mu\tau$ product for holes, the performances of these four cells can be explained.

As a result, the hole transport is improved in the a-SiGe cell and reduced in the a-SiC cell by the bandgap profiling. It can be considerd that these performances are caused by the increase of the electric field for holes within the cell and the spatial distribution of $\mu\tau$ product for holes.

The AM1, 100mW/cm^2 light was irradiated to the a-SiGe Type P,N and a-SiC Type P,N cells from the p layer sides. The cell performances are shown in Table III. In the a-SiGe cells, the output power of Type P cell is larger than that of type N cell and this result agree with the performance which is shown in Fig.4. In the a-SiC cells, the output power of the Type P cell is larger than that of the Type N cell in spite of the poor hole transport. This experimental result can not be explained by the hole transport.

In both a-SiGe cells and a-SiC cells, since the output powers of the Type P cells are larger than those of the Type N cells, the distribution of photogeneration was investigated.

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Table III Cell p
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Table I Cell performances of a-SiGe Type P,N and a-SiC Type P,N cells under blue light from n layer side.

AM1 100mW/cm² through a blue (<420nm) cut-on filter						
Cell type			Isc	Voc	F.F.	Pmax
			mA/cm²	V		mW/cm²
a-SiGe	Type P	p n ⇦	1.34	0.517	0.522	0.36
	Type N	p n ⇦	0.82	0.681	0.477	0.27
a-SiC	Type P	p n ⇦	0.65	0.804	0.420	0.22
	Type N	p n ⇦	0.76	0.828	0.550	0.35

Table II Cell performances of a-SiGe Type P,N and a-SiC Type P,N cells under blue light from p layer side.

AM1 100mW/cm² through a blue (<420nm) cut-on filter						
Cell type			Isc	Voc	F.F.	Pmax
			mA/cm²	V		mW/cm²
a-SiGe	TYPE P	⇨ p n	2.37	0.584	0.546	0.76
	TYPE N	⇨ p n	2.17	0.767	0.545	0.91
a-SiC	TYPE P	⇨ p n	1.97	0.882	0.670	1.16
	TYPE N	⇨ p n	1.79	0.856	0.627	0.96

Table III Cell performances of a-SiGe Type P,N and a-SiC Type P,N cells under AM 1, 100 mW/cm² light from p layer side.

AM1 100mW/cm²						
Cell type			Isc	Voc	F.F.	Pmax
			mA/cm²	V		mW/cm²
a-SiGe	Type P	⇨ p n	19.5	0.669	0.489	6.37
	Type N	⇨ p n	14.0	0.841	0.472	5.56
a-SiC	Type P	⇨ p n	11.3	0.949	0.618	6.63
	Type N	⇨ p n	11.2	0.933	0.597	6.26

Distribution of photogeneration

To evaluate the effect of bandgap profiling on the light absorption, the light intensity change by the absorption and the distribution of the light absorption amount were calculated. The calculated data in the a-SiGe Type P, N and 1.52 eV constant bandgap cells under 690nm light are shown in Fig.10 (a),(b). These results show that the distribution of the light absorption amount corresponds closely with the bandgap profiles under the long wavelength light. In other words, we can designed the distribution of photogeneration by using the bandgap profiling, especially under the long wavelength light. As a result, the light is absorbed in the narrow bandgap region near the p layer of the a-SiGe Type P cell and the carriers are photogenerated near the p layer and the collection efficiency of holes is increased.

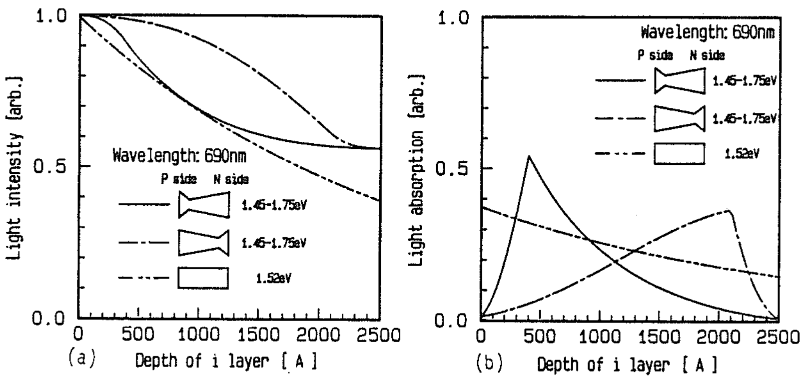

Fig.10 Calculated light intensity change (a) and distribution of light absorption (b) in a-SiGe Type P,N and 1.52 eV constant bandgap cell under 690nm light.

To confirm the effect of light absorption, a well type potential cell was made as shown in Fig.11. It is considered that there is not the increase of the electric field within the cell at this cell structure. The long wavelength light is almost absorbed at narrow bandgap layer which we named " carrier generating layer " as shown in Fig.12. The F.F. of the well type cell were improved compared with that of the constant bandgap cell as shown in Fig.13. As a result, it is considered that the distribution of light absorption is the most effective cause.

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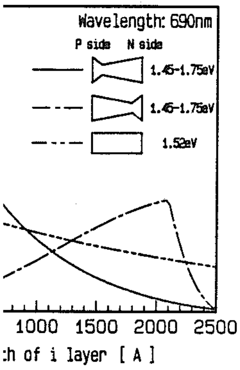

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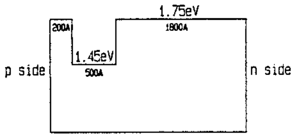

Fig.11 Bandgap profiles of well type cell

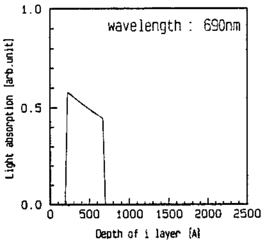

Fig.12 Distribution of light absorption in well type cell

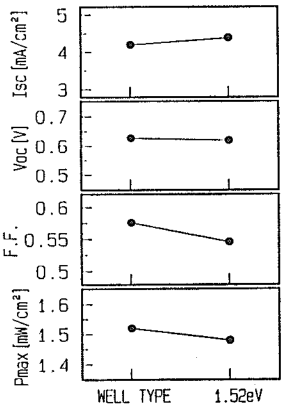

Fig.13 Performances of well type cell and constant bandgap cell

Effect of bandgap profiling on cell performance

Performances of a-Si solar cells is usually dtermined by a performance of holes, which are " limiting carrier ", because a hole mobility is smaller than a electron mobility [7]. It is considered that a limiting carrier of a-SiGe and a-SiC cell in this case is also holes. Therefore, to improve the cell performance, it is important to improve the hole collection even if the electron collection is reduced slightly.

On the basis of that idea, the analytical results about the effect of the bandgap profiling on the cell performance are summarized in Table IV. A upward arrow means a positive effect and a downward arrow means a negative effect on the cell performance. It can be considerd that the carrier transport are changed by the increase of electric field for holes within the cell and the spatial distribution of μt products of holes and electrons. The hole transport is improved in the a-SiGe cell and reduced in the a-SiC cell by the bandgap profiling. The distriubution of photogeneration can be designed and the carriers can be photogenerated near the p layer by using the bandgap profiling.

In the a-SiGe cell, all causes by the bandgap profiling have the positive effect on the cell performance. In the a-SiC cell, in spite of the poor hole transport and the less effect by the distribution of photogeneration, bandgap profiling also has positive effect.

In conclusion from the analysis, the bandgap profiling affect the carrier tansport and the distribution of photogeneration. And, the most important contribution to the cell performance is an optimization of the ambipolar carrier collection by the bandgap profiling.

Table IV Effect of bandgap profiling on the cell performance.

			a-SiGe cell	a-SiC cell
ambipolar carrier collection	Carrier Transport	Electric Field	⇧	⇧
		Distribution of $\mu\tau$ product	⇧	⇩
	Distribution of photogen.	Distribution of light absorption	⇧	⇧
Total Effect			⇧	⇧

Bandgap profile design of a-SiGe cell

On the basis of the analytical results, the bandgap profiling of a-SiGe cells was investigated. The minimum bandgap was decreased from 1.50 eV to 1.39 eV to increase the carriers which were generated near p layer. The total i layer thickness is 2500 A and the maximum bandgap at the both interfaces is 1.74 eV. The performances under red light (AM1, 100 mW/cm^2 light through a red (>660nm) cut-on-filter) are shown in Fig.14. The short circut current increased remarkably and F.F. decrease slightly as the minimum bandgap decrease. The output power is almost constant, but the largest short circuit current with decreasing bandgap was 7.1 mA/cm^2. This cell is suitable to adjust the current of each component cell at a stacked cell, because the short circuit currents of the other component cells are more than 7 mA/cm^2.

Bandgap profile design of a-SiC cell

The bandgap profiling of a-SiC cell was also investigated. The output powers of a-SiC cells with a narrow bandgap near p layer are larger than those of the cells with a narrow bandgap near the n layer, as shown in Table III.

The minimum bandgap of the a-SiC cell were decreased from 1.99 eV to 1.80 eV to increase the carriers which were generated near p layer. The total i layer thickness is about 1300 A and the maximum bandgap at the both interfaces is 1.98 eV. The performances under AM1 light are shown in Fig.15. The F.F. and short circuit current increase and open circuit voltage decrease slightly as the minimum bandgap decrease. As a result, a-SiC cell with high F.F. and high open circuit voltage was obtained.

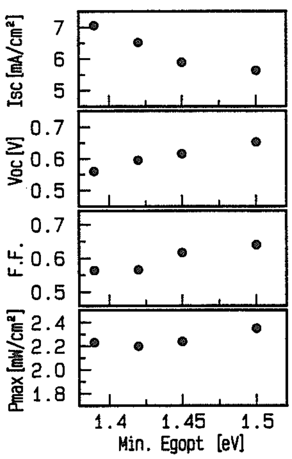

Fig.14 Performances of a-SiGe cells with bandgap profiling versus the minimum bandgap

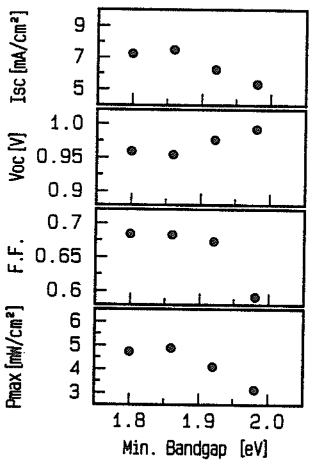

Fig.15 Performances of a-SiC cells with bandgap profiling versus the minimum bandgap

a-SiC/a-Si/a-SiGe mult

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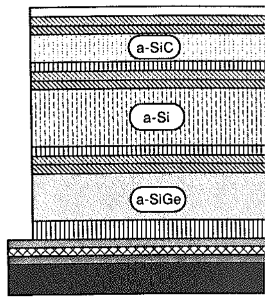
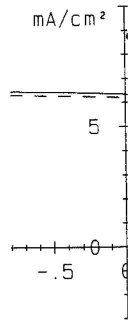


Fig.16 a-SiC/a-Si/a-SiG
multi-bandgap st
cell structure



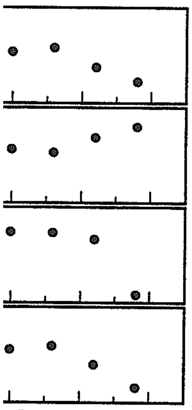
SiC/Si/SiGe
SiC/Si/SiGe

Fig.18 Pe
mu

bandgap profiling of a-SiGe
was decreased from 1.50 eV
nerated near p layer. The
num bandgap at the both
ed light (AM1, 100 mW/cm²
hown in Fig.14. The short
ase slightly as the minimum
onstant, but the largest
7.1 mA/cm². This cell is
t cell at a stacked cell,
nponent cells are more than

investigated. The output
p layer are larger than
n layer, as shown in Table

decreased from 1.99 eV to
rated near p layer. The
aximum bandgap at the both
r AM1 light are shown in
increase and open circuit
decrease. As a result,
ltage was obtained.



rmances of a-SiC cells
bandgap profiling
is the minimum bandgap

a-SiC/a-Si/a-SiGe multi-bandgap stacked cell

On the basis of the investigation of a-SiGe and a-SiC cells with bandgap profiling, we made an a-SiC/a-Si/a-SiGe multi-bandgap stacked cell with bandgap profiling. The cell structure and bandgap profiles are shown in Fig.16 and Fig.17. The bandgap profiling was applied to the a-SiC and a-SiGe component cells. The efficiency of the multi-bandgap cell with bandgap profiling is 10.1% as shown in Fig.18. This value is improved compared with 8.6% of the cell without bandgap profiling. The F.F. is improved by the bandgap profiling and the open circuit voltage is improved by using the wide bandgap materials at the a-SiC cell.

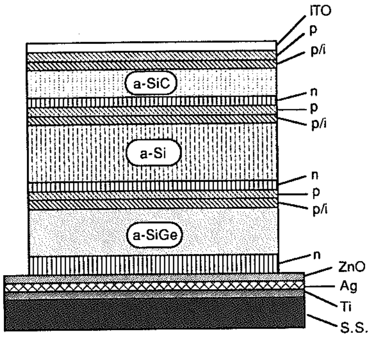


Fig.16 a-SiC/a-Si/a-SiGe multi-bandgap stacked cell structure

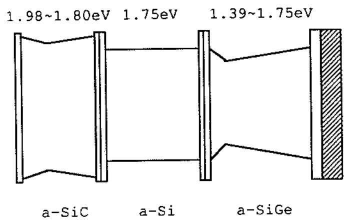
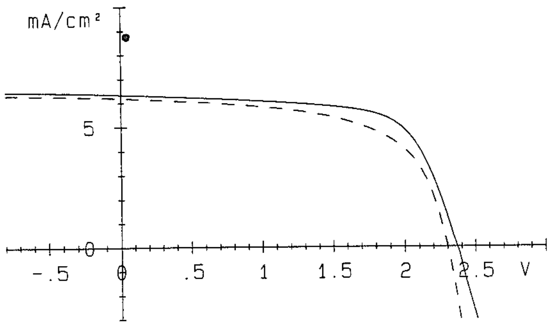


Fig.17 Bandgap profiles of multi-bandgap cell



	Egopt (eV)	Isc (mA/cm²)	Voc (V)	F.F.	Pmax (mW/cm²)
SiC/Si/SiGe	1.98-1.80/1.75/1.39-1.75	6.3	2.37	0.67	10.1
SiC/Si/SiGe	1.90/1.75/1.55	6.2	2.33	0.59	8.6

Fig.18 Performances of a-SiC/a-Si/a-SiGe multi-bandgap stacked cell

CONCLUSIONS

It has been shown from the analysis that the bandgap profiling affect the carrier transports and the distribution of photogeneration, therefore ambipolar carrier property can be controlled by the bandgap profiling.

The most important contribution to the cell performance is an optimization of the ambipolar carrier collection by the bandgap profiling.

A promising a-SiC/a-Si/a-SiGe multi-bandgap stacked cell with 10.1% efficiency was demonstrated.

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PROSPECTS OF

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ABSTRACT

The transport
are found to be l
relationship betw
Ge and H content)
decreases with in
content. The rel
composition is de
extent of gas pha
hydrogen radical
electronic transp
gap are used to s
cell performance.
both hole and ele
performance loss

INTRODUCTION

Amorphous sil
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deposit uniform t
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of amorphous sili
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can be found. On
problem is the tr
solar cells have
Improvements in s
solar cells emplo
stacked together.
preparation of hi
be traced to the
designs optimized
adapted for a-SiG
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of the alloys is
Solar cell de
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