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# Multi junction solar cells using band-gap induced cascaded light absorption

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We propose multi junction solar cells using an optical reflection system formed by arranging plural solar cells in decreasing order of their band gaps for achieving cascaded light absorption by their own band gaps: the first solar cell absorbs some light with a photon energy higher than the highest band gap and reflects the residual light with a lower photon energy to the second solar cell. We further propose to use plural batteries for charging electrical power generated by the individual solar cells to overcome the current matching problem in the multi-junction solar cells. We experimentally demonstrated reflection-type multi junction solar cells using commercially available hydrogenated amorphous silicon (a-Si:H) and crystalline silicon (c-Si) solar cells using air mass 1.5 light illumination. A high open circuit voltage of 24.3 V was achieved, which was a sum of 19.3 and 5.0 V for the individual a-Si:H and c-Si solar cells. However, since there was no current matching between the a-Si:H and c-Si solar cells, the a-Si:H–c-Si serially connected solar cell gave a maximum power of 0.057 W, which was lower than 0.063 W, the sum of those for the individual a-Si:H and c-Si solar cells. The method of charging electrical power from individual solar cells is useful to efficiently achieve electrical power from individual a-Si:H and c-Si solar cells in the absence of current matching in multi junction solar cells.


## 1. Introduction

Crystalline silicon solar cells have been widely developed as devices for generating electrical power directly from sunlight.[1–4] Because crystalline silicon has a band-gap energy of 1.12 eV at room temperature, which locates in the energy tail region of the sun light spectrum on the earth with the air mass (AM) 1.5 condition, crystalline silicon effectively absorbs sunlight with a photon energy higher than its band gap. However, crystalline silicon solar cells have the limitation of the power conversion efficiency of 33.7%:[5] this indicates that 66.3% of the sunlight power does not contribute to the generation of electrical power. When light with a photon energy higher than the band gap is absorbed, hole and electron pairs are generated in silicon solar cells. The hole and electron pairs lose their energy to the band gap energies, and the open circuit voltage $V_{oc}$ is limited by the built-in potential in the solar cells. Light with a very high photon energy is therefore not efficient for producing electrical power using silicon solar cells. To solve this problem and increase the conversion efficiency, multi junction solar cells combined with large- and small-band-gap semiconductors have been widely developed.[6–22] An epitaxial crystalline growth method has been widely studied to fabricate large-band-gap pn junction layers on small-band-gap pn junction layers. On the other hand, the method of stacking individual solar cells using conductive and transparent gels has also been investigated.[17,18]

In this paper, we propose a simple reflection-type multi junction solar cell system using individual solar cells with different band gaps.[23] We first discuss the principle of the present method. It consists of reflection-type optic for realizing simultaneously specific absorptions of semiconductor solar cells with different band gaps. The electrically series connection among those individual cells simply forms multi junction solar cells. Moreover, we propose the battery charging of the electrical power of the individual solar cells to solve the electrical current matching problem. Then, we report experimental demonstrations of the present reflection-type multi junction solar cells. Using experimental results, we discuss an effective power generation method by separately battery charging each solar cell in the multi junction solar cell system.

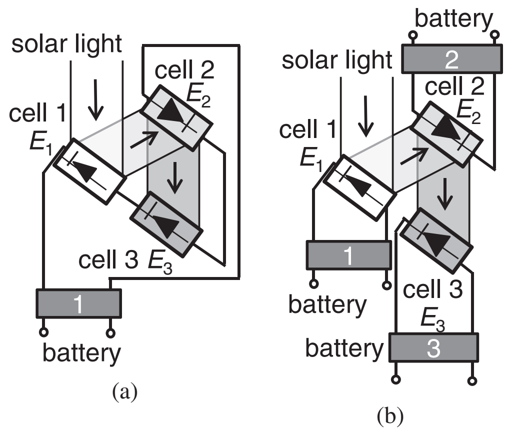


**Fig. 1.** Schematic images for reflection-type optic with three different solar cells, which were (a) electrically connected with electrical wires, and (b) separately connected to batteries.

## 2. Principle of the present multi junction solar cells

We discuss three different solar cells named cell 1, cell 2, and cell 3. Their band-gap energies $E_1$, $E_2$, and $E_3$ are assumed to be high, intermediate, and low ($E_1 > E_2 > E_3$), respectively. A reflection-type optic is constructed with those cells, as shown in Fig. 1. Light is first illuminated to cell 1 with $E_1$. Cell 1 absorbs some light with photon energy higher than $E_1$ and generates electrical power. On the other hand, the residual light with a photon energy lower than $E_1$ is not absorbed by cell 1. It is reflected outside of cell 1. If metal electrodes are formed on the rear surface of the solar cell or a mirror is placed on the rear side, the light with a photon energy lower than $E_1$ is effectively reflected by metal electrodes or the mirror and comes out from cell 1. The light reflected from cell 1 is illuminated to cell 2 with a band gap of $E_2$ lower than $E_1$. Cell 2 absorbs some light with a photon energy between $E_1$ and $E_2$, and reflects the residual light with a photon energy lower than $E_2$. The light reflected from cell 2 is illuminated to cell 3 with a band gap of $E_3$

 

lower than $E_2$. Cell 3 absorbs some light with a photon energy higher than $E_3$. Therefore, this reflection optic makes it possible to automatically select light for the generation of electrical power using each solar cell component.

When the solar cells 1, 2, and 3 are connected to each other by electrical wires while keeping the series configuration of pn–pn junctions, as shown in Fig. 1(a), the reflection optic and electrically series connection simply form a three-junction solar cell with two output terminals. The three solar cells generate electrical power by absorbing light with a photon energy specifically selected by their own band gaps. This indicates that sunlight is effectively used for generating electrical power using the present system with different single junction solar cells. A high $V_{oc}$ value results from the sum of the $V_{oc}$ values of the three cell. On the other hand, the short circuit current $I_{sc}$ of the serially connected three-junction solar cell shown in Fig. 1(a) is governed by the minimum $I_{sc}$ among the three solar cells, which is the so called current matching problem.[24–26] It is important to select solar cells with appropriate band gaps to achieve similar $I_{sc}$ values among the solar cells.

To overcome the current matching problem, we further propose the use of plural batteries for charging electrical power generated by the solar cells in the present reflection-type cell, as shown in Fig. 1(b). Plural batteries are used to charge the electrical power generated by each solar cell, and there is no electrical connection among individual solar cells, although a single battery is used to charge the electrical power from the multi junction solar cell with the two output terminal shown in Fig. 1(a). Since the efficiency of charging electrical power by a battery is generally high, it is possible for a combination of the present light reflection optic by solar cells with batteries to effectively generate electrical power from the sunlight.

## 3. Experimental procedure

Commercially available 28 serially connected hydrogenated amorphous silicon (a-Si:H) solar cell and 6 serially connected crystalline silicon (c-Si) solar cell were applied to fundamentally demonstrate the present reflection-type multi junction solar cells. The a-Si:H solar cell had a structure of transparent oxide electrode (TCO) layer/n-type a-Si:H layer/1.5-µm-thick intrinsic a-Si:H layer/p-type a-Si:H layer/TCO layer/textured glass substrate with an area of 50 cm$^2$. The a-Si:H layers were formed by plasma-enhanced chemical vapor deposition. Because an organic opaque resin was coated over the top TCO layer, light was illuminated to the a-Si:H cell through the glass substrate for measurements of optical reflectivity and solar cell characteristics. The c-Si solar cell had a structure of silver grid electrodes/n-doped region/200-µm-thick p-type substrate/p$^+$-doped region/silver electrode with an area of 60 cm$^2$. A texture structure and an antireflection layer were formed on the surface. The reflectivity spectra of a-Si:H and c-Si cells were measured using a spectrometer (Nihonbunko V-670) between 250 and 2000 nm by light illumination normally to the cells using an integrating sphere in order to confirm band-gap-induced optical absorption. The a-Si:H and c-Si solar cells were connected to each other using an electric wire to form a two-terminal a-Si:H–c-Si-electrically connected solar cell with a pn–pn configuration. Those cells were placed facing

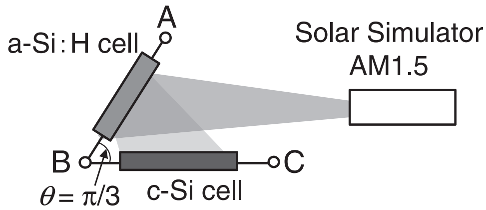


**Fig. 2.** Schematic image for reflection-type optic using a-Si:H and c-Si solar cells, which were placed facing each other with an angle of $\pi/3$ radian and connected by electric wires.

each other with an angle $\theta$ of $\pi/3$ radian, as shown in Fig. 2. An AM 1.5 light beam (Asahibunko HAL-320W) at 50 mW/cm$^2$ with a cross section of 25 cm$^2$ was illuminated to the a-Si:H solar cell. The center of the light beam was parallel to the surface of the c-Si solar cell, as shown in Fig. 2. The incident angle of the center of the light beam to the a-Si:H solar cell was $|\pi/2 - \theta|$ radian. The reflection light from the a-Si:H solar cell was subsequently illuminated to the c-Si solar cell, as shown in Fig. 2. The incident angle of the center of the light beam to the c-Si solar cell was therefore $|\pi/2 - 2\theta|$ radian. Although the angle $\theta$ is changeable, $\theta$ was set at $\pi/3$ radian in this demonstration to keep the same incident angle of $\pi/6$ radian for the a-Si:H and c-Si solar cells. Because the light beam was dispersed at about $\pi/18$ rad in reality, the light intensity was not completely uniform over the solar cell surface. The electrical current as a function of voltage (*I–V*) was measured for the a-Si:H solar cell between the terminals A and B shown in Fig. 2 and the c-Si solar cell between the terminals B and C using an Agilent 4156C semiconductor parameter analyzer. Moreover, *I–V* characteristics were also measured for the a-Si:H–c-Si electrically connected cell between the terminals A and C.

## 4. Results and discussion

Figure 3 shows optical reflectivity spectra of the a-Si:H and c-Si solar cells. The low optical reflectivity between 5 and 10% was observed between 250 and 670 nm for the a-Si:H solar cell because of the absorption of the band transition of a-Si:H. An increase in reflectivity was observed at 670 nm, which corresponds to the band gap of 1.85 eV for the a-Si:H solar cell. The optical reflectivity ranged from 23 to 46% for wavelengths longer than 670 nm. It was not very high because there was an optical absorption by the organic resin coated over the surface of the a-Si:H solar cell. The low optical reflectivity between 5 and 12% was observed between 250 and 1100 nm for the c-Si solar cell. An increase in reflectivity was observed at 1100 nm, which corresponds to the band gap of 1.1 eV for the c-Si solar cell. The results in Fig. 3 suggested that the light with wavelengths below 670 nm was effectively absorbed in the a-Si:H solar cell with the high band-gap energy. The light with wavelengths above 670 nm was reflected from the a-Si:H solar cell and illuminated to the c-Si solar cell. Some light with a wavelength between 670 and 1100 nm was absorbed in the c-Si solar cell with the low band-gap energy by the reflection system shown in Fig. 2. However, the absolute values of optical reflectivity in the case of the incident angle of $\pi/6$ shown in Fig. 2 were not determined using the present spectrometer because it was limited by normal light

 

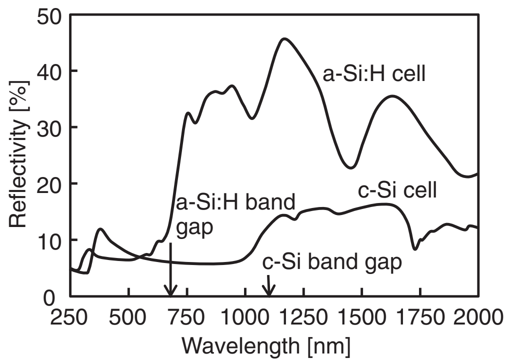


**Fig. 3.** Optical reflectivity spectra of the a-Si:H and c-Si solar cells.

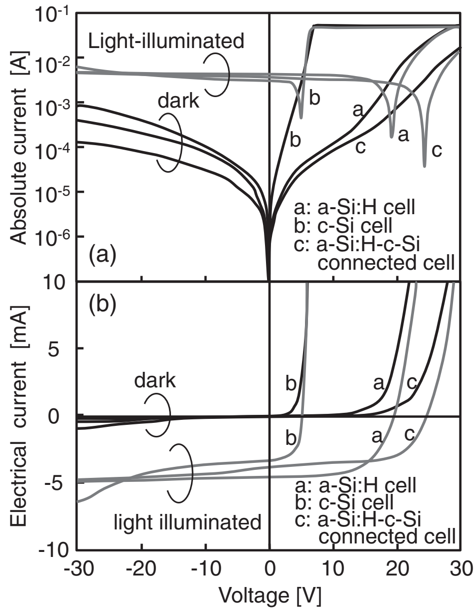


**Fig. 4.** (a) Logarithmic plot of absolute electrical current and (b) linear plot of electrical current as functions of applied voltages for the a-Si:H, c-Si, and a-Si:H–c-Si connected solar cells.

illumination. The investigation of the dependence of the incident angle of light is a future work.

Figure 4 shows logarithmic plots of absolute electrical current (a) and linear plots of electrical current (b) as functions of voltages applied between terminals A and B, B and C, and A and C for the a-Si:H, c-Si, and a-Si:H–c-Si connected solar cells, respectively, when the samples were in the dark and illuminated with AM 1.5 light, as shown in Fig. 2. Diode rectified characteristics were observed in the dark in all measurement cases, as shown in Fig. 4(a). The absolute electrical current increased as the voltage increased in the dark for every solar cell. The c-Si solar cell had the highest dark current. The a-Si:H–c-Si serially connected solar cell naturally had the lowest dark current owing to the series connection that increased impedance. Light illumination generated photo induced current, as shown in Figs. 4(a) and 4(b). The a-Si:H solar cell had the highest photo induced current at 0 V, which corresponded to $I_{sc}$. The c-Si solar cell had the lowest photo induced current at 0 V because a low light intensity was illuminated to the c-Si solar cell owing to the low reflectivity between 670 and 1100 nm induced by

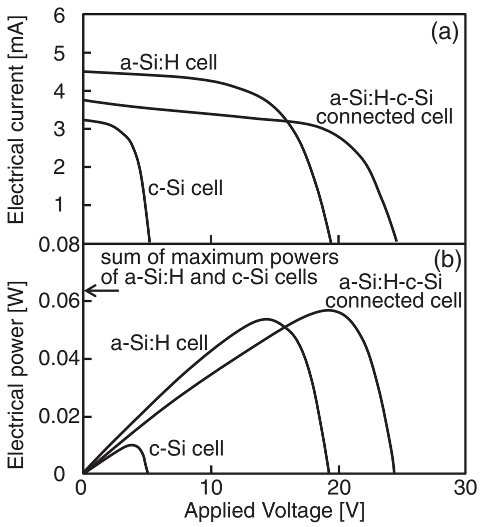


**Fig. 5.** (a) Solar cell characteristics and (b) electrical powers as functions of applied voltage for the a-Si:H, c-Si, and a-Si:H–c-Si connected solar cells.

photo absorption by resin coating the rear surface of the a-Si:H solar cell. The a-Si:H–c-Si serially connected solar cell had a highest voltage with no photo induced current, which corresponded to $V_{oc}$. The multi junction solar cell was clearly realized by the present simple reflection-type system shown in Figs. 1 and 2. The photo-induced currents of the a-Si:H and c-Si solar cell at around 0 V did not level off but slightly increased as the applied voltage increased probably because of the low parallel resistances of the solar cells, as shown in Fig. 4(b).

Figure 5 shows (a) solar cell characteristics obtained from the *I–V* results shown in Fig. 4 and (b) electrical powers as functions of applied voltage. Typical solar cell current voltage characteristics were obtained in all measurement cases. The a-Si:H–c-Si serially connected solar cell had a $V_{oc}$ of 24.3 V, which was a sum of 19.3 and 5.0 V for the individual a-Si:H and c-Si solar cells. The present optical reflection-type system resulted in multi junction solar cells. However, the $I_{sc}$ of the c-Si solar cell was $3.3 \times 10^{-3}$ A, which was lower than that of the a-Si:H solar cell ($4.5 \times 10^{-3}$ A). There was no current matching between the a-Si:H and c-Si solar cells. In the case of the series connection of the a-Si:H and c-Si solar cells, the electrical current was determined by voltage balance and current coincidence in each applied voltage case. The applied voltage at terminals A and C must be the same as the sum of the voltages biased at the a-Si:H and c-Si solar cells. Simultaneously, the same electrical current must flow to the a-Si:H and c-Si solar cells. $I_{sc}$ of the a-Si:H–c-Si serially connected solar cell was $3.8 \times 10^{-3}$ A, which was slightly higher than that of the c-Si solar cell. This resulted from the fact that the a-Si:H and c-Si solar cells were automatically biased by 14.0 and $-14.0$ V to achieve the coincident current condition between the a-Si:H and c-Si solar cells in the short circuit case because the photo-induced current slightly changed with the voltage in the low voltage region for the a-Si:H and c-Si solar cells, as shown in Figs. 4(b) and 5(a).

The electrical powers of the a-Si:H, c-Si, and a-Si:H–c-Si serially connected solar cells increased as the applied voltage increased, as shown in Fig. 5(b). The maximum electrical power was 0.057 W for the a-Si:H–c-Si serially connected solar cell. Although it was higher than of the a-Si:H solar cell (0.053 W), it was lower than the sum of those of individual a-Si:H and c-Si solar cells (0.063 W), as shown by the arrows in Fig. 5(b) because of the absence of current matching. The additional idea of charging electrical power from individual solar cells shown in Fig. 1(b) is useful for solving the current matching problem and efficiently realizing the same electrical power as the sum of those of individual a-Si:H and c-Si solar cells, which are components of the reflection-type optic. If their electrical powers are independently charged by batteries, the a-Si:H and c-Si solar cells equally contribute to power generation and the total electrical power can be 0.063 W.

The present experimental results demonstrated a multi junction solar cell by the cascade-type self-photo absorption of solar cells associated with their optical band gaps. Moreover, the problem of the absence of current matching among individual solar cells in the multi junction solar cell is solved by an additional idea of battery charging electrical power from individual solar cells. The present idea allows a multi junction solar cell to have many solar cells with different band gaps from high to low energies to effectively use solar light power because the electrical current coincidence among the individual solar cells is not required in the case of battery charging each solar cell, as shown in Fig. 1(b).

## 5. Conclusions

We proposed reflection-type multi junction solar cells with different band gaps. An optical reflection system is formed by arranging plural solar cells in decreasing order of their band gaps. Light is first illuminated to a solar cell with the highest band gap. Some light with a photon energy higher than the band gap is absorbed, while the residual light with a lower photon energy is reflected outside of the solar cell and illuminated to the second solar cell with the second highest band gap. Then, some light with a photon energy between the highest and second highest band gaps is absorbed, while the residual light with a photon energy lower than the second highest band gap is reflected outside of the second solar cell. In the same manner, cascaded light absorption is achieved by the reflection-type optic constructed with solar cells. To overcome the current matching problem in the multi junction solar cell, we further proposed the use of plural batteries for charging electrical power generated by the individual solar cells in the present reflection system. Commercially available 28 serially connected a-Si:H solar cell and 6 serially connected c-Si solar cell were applied to fundamentally demonstrate the present reflection-type multi junction solar cells. An AM 1.5 light beam at 50 mW/cm$^2$ and with a cross section of 25 cm$^2$ was slantwise illuminated to the a-Si:H solar cell with an incident angle of $\pi/6$ radian. Optical reflectivity measurement indicated that light with a wavelength shorter than 670 nm corresponding to the band gap of 1.85 eV of the a-Si:H solar cell was absorbed in the a-Si:H solar cell, and that the light with a longer wavelength was reflected and subsequently illuminated to the c-Si solar cell. The a-Si:H–c-Si serially connected solar cell formed with electrical wires had a $V_{oc}$ of 24.3 V, which was the sum of those of the individual a-Si:H and c-Si solar cells. This indicates the present optical reflection-type system demonstrated multi junction solar cells. However, since there was no current matching between the a-Si:H and c-Si cells, the a-Si:H–c-Si serially connected solar cells gave a maximum power of 0.057 W, which was lower than the sum of those of the individual a-Si:H and c-Si solar cells (0.063 W). The method of charging electrical power from individual solar cells is useful for efficiently achieving electrical power from individual a-Si:H and c-Si solar cells in the absence of current matching in multi junction solar cells.

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1) A. Rohatagi, Proc. 3rd World Conf. Photovoltaic Energy Conversion, 2003, A29.
2) M. A. Green, Prog. Photovoltaics **17**, 183 (2009).
3) M. A. Green, K. Emery, Y. Hishikawa, W. Warta, and E. D. Dunlop, Prog. Photovoltaics **17**, 12 (2011).
4) J. Zhao, A. Wang, M. A. Green, and F. Ferrazza, Appl. Phys. Lett. **73**, 1991 (1998).
5) W. Shockley and H. J. Queisser, J. Appl. Phys. **32**, 510 (1961).
6) K. Yamamoto, Sol. Energy Mater. Sol. Cells **66**, 117 (2001).
7) K. Nishioka, T. Takamoto, T. Agui, M. Kaneiwa, Y. Uraoka, and T. Fuyuki, Jpn. J. Appl. Phys. **43**, 882 (2004).
8) F. Meillaud, A. Shah, C. Droz, E. Vallat-Sauvain, and C. Miazza, Sol. Energy Mater. Sol. Cells **90**, 2952 (2006).
9) S. P. Bremner, M. Y. Levy, and C. B. Honsberg, Prog. Photovoltaics **16**, 225 (2008).
10) H. Sugiura, C. Amano, A. Yamamoto, and M. Yamaguchi, Jpn. J. Appl. Phys. **27**, 269 (1988).
11) J. M. Olson, S. R. Kurtz, A. E. Kibbler, and P. Faine, Appl. Phys. Lett. **56**, 623 (1990).
12) T. Takamoto, E. Ikeda, H. Kurita, M. Ohmori, M. Yamaguchi, and M. J. Yang, Jpn. J. Appl. Phys. **36**, 6215 (1997).
13) M. Yamaguchi, K. Nishimura, T. Sasaki, H. Suzuki, K. Arafune, N. Kojima, Y. Ohsita, Y. Okada, A. Yamamoto, T. Takamoto, and K. Araki, Sol. Energy **82**, 173 (2008).
14) R. R. King, D. C. Law, K. M. Edmondson, C. M. Fetzer, G. S. Kinsey, H. Yoon, R. A. Sherif, and N. H. Karam, Appl. Phys. Lett. **90**, 183516 (2007).
15) M. Yoshimi, T. Sasaki, T. Sawada, T. Suezaki, T. Meguro, T. Matsuda, K. Santo, K. Wadano, M. Ichikawa, A. Nakajima, and K. Yamamoto, Proc. 3rd World Conf. Photovoltaic Energy Conversion, 2003, p. 1566.
16) W. Guter, J. Schone, S. P. Philipps, M. Steiner, G. Siefer, A. Wekkeli, E. Welser, E. Oliva, and M. Yamaguchi, Sol. Energy Mater. Sol. Cells **75**, 261 (2003).
17) J. Takenezawa, M. Hasumi, T. Sameshima, T. Koida, T. Kaneko, M. Karasawa, and M. Kondo, Ext. Abstr. Int. Conf. Solid State Devices and Materials, 2010, I-8-4.
18) T. Sameshima, J. Takenezawa, M. Hasumi, T. Koida, T. Kaneko, M. Karasawa, and M. Kondo, Jpn. J. Appl. Phys. **50**, 052301 (2011).
19) W. Guter, J. Schone, S. P. Philipps, M. Steiner, G. Siefer, A. Wekkeli, E. Welser, E. Oliva, A. W. Bett, and F. Dimroth, Appl. Phys. Lett. **94**, 223504 (2009).
20) N. E. Posthuma, J. van der Heide, G. Flamand, and J. Poortmans, IEEE Trans. Electron Devices **54**, 1210 (2007).
21) T. Kaneko and M. Kondo, Jpn. J. Appl. Phys. **52**, 04CR04 (2013).
22) M. Yamaguchi, K.-I. Nishimura, T. Sasaki, H. Suzuki, K. Arafune, N. Kojima, Y. Oshita, Y. Okada, A. Yamamoto, T. Takamoto, and K. Araki, Sol. Energy Mater. **82**, 173 (2008).
23) T. Sameshima, S. Yoshidomi, and M. Hasumi, Ext. Abstr. 2013 JSAP–MRS Joint Symp., 2013, 16p-PM2-3.
24) S. R. Kurtz, P. Faine, and J. M. Olson, J. Appl. Phys. **68**, 1890 (1990).
25) N. H. Karam, R. R. King, B. T. Cavicchi, D. D. Krut, J. H. Ermer, M. Haddad, C. Li, D. E. Joslin, M. Takahashi, J. W. Eldredge, W. T. Nishikawa, D. R. Lillington, B. M. Keyes, and R. K. Ahrenkiel, IEEE Trans. Electron Devices **46**, 2116 (1999).
26) W. E. McMahon, K. E. Emery, D. J. Friedman, L. Ottoson, M. S. Young, J. S. Ward, C. M. Kramer, A. Duda, and S. Kurtz, Prog. Photovoltaics **16**, 213 (2008).