Open circuit voltage improvement of high-deposition-rate microcrystalline silicon solar cells by hot wire interface layers

Y. Mai,[a),b)] S. Klein, R. Carius, and H. Stiebig
IPV, Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany

X. Geng
Institute of Photoelectronics, Nankai University, Tianjin 300071, People's Republic of China

F. Finger
IPV, Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany

(Received 22 April 2005; accepted 28 June 2005; published online 9 August 2005)

Significant improvement in open circuit voltage and fill factor was achieved for microcrystalline silicon (μc-Si:H) solar cells deposited by plasma-enhanced chemical vapor deposition (PECVD) by the incorporation of an intrinsic μc-Si:H p/i buffer layer fabricated by hot-wire (HW) CVD. The improved p/i interface quality, likely due to the ion-free deposition on the p layers in the HWCVD process, was concluded from a considerably enhanced blue light response in such solar cells. Using this buffer layer concept allows the authors to apply high deposition rate PECVD processes for the μc-Si:H i layer material, yielding a high efficiency of 10.3% for a single junction μc-Si:H solar cell. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2011771]

Hydrogenated microcrystalline silicon (μc-Si:H) solar cells with a high open circuit voltage (V_{OC}) are of great importance to achieve high conversion efficiency. Although not solely determined by the i layer crystallinity, the V_{OC} of μc-Si:H solar cells were found to increase with the amorphous volume fraction.[1–3] However, the excessive amorphous phase leads to a severe drop of the cell performance,[1–3] probably due to the carrier transport hindrance in the amorphous phase.[4] On the other hand, highly crystalline μc-Si:H material usually shows bad qualities, such as high defect density, etc.[5] Therefore, optimum μc-Si:H solar cells are always obtained with intermediate crystallinity.[1–3]

The two most common methods to prepare μc-Si:H thin films and solar cells are plasma-enhanced chemical vapor deposition (PECVD) and Hot-Wire (HW) CVD.[1–3,6–12] Although both methods yield high material quality, the corresponding solar cells show distinct differences in their performance. PECVD μc-Si:H solar cells show a sharp performance deterioration as the V_{OC} exceeds the typical value of $\sim$530 mV of the optimum cells,[1,3,6,7] while solar cells deposited by HWCVD at a low substrate temperature maintain high performance at a higher V_{OC} up to 600 mV.[2] Comparing the PECVD and HWCVD solar cells at similar i layer crystallinity reveals that they exhibit very similar bulk i layer quality, and that the differences between them can be attributed to a more effective carrier extraction at the p/i interface of the HWCVD solar cells.[13] In the present paper it will be shown how by using a buffer layer at the p/i interface deposited by HWCVD in a PECVD solar cell improves the short-wavelength response and eliminates the differences between HWCVD and PECVD solar cells by increasing V_{OC} and fill factor (FF) of the latter. Using such buffer layers allows the authors to apply high deposition rate (R_D) PECVD processes for the μc-Si:H i layer material, yielding single junction solar cell efficiency above 10%.

Three solar cells series with (i) HWCVD i layers, (ii) PECVD i layers, and (iii) PECVD i layers with 100 nm μc-Si:H HWCVD p/i buffer layers, were prepared on similar substrates, with identical doped layers and similar total i layer thickness. The silane concentration, $SC = [SiH_4]/([SiH_4]+[H_2])$, defined by the gas flow ratio of silane and hydrogen was varied in each case to adjust the structure mixture of the i layer material from highly crystalline to amorphous growth. All solar cells were deposited in a multichamber system[2] in a p-i-n sequence on 10×10 cm^2 texture-etched ZnO-coated glass substrates.[14] The μc-Si:H p layer and amorphous n layer were prepared by PECVD in separate chambers. The i layers of HWCVD solar cells were deposited with two tantalum filaments at the temperature of 1650 °C, resulting in a substrate temperature of $\sim$185 °C at a gas pressure of 3.5 Pa. The R_D was about 1 Å/s. PECVD i layers were prepared with a very high frequency of 94.7 MHz. In the low-pressure, low-power regime "lplP," used for the majority of the PECVD samples, the working pressure, discharge power, and substrate temperature were 0.25 hPa, 10 W, and 200 °C, respectively, resulting in a R_D of about 2 Å/s. In addition, PECVD i layers were deposited in the high-pressure, high-power "hphP" regime at 2.1 hPa and 60 W at a R_D of 11 Å/s.[3] Deposition parameters of the HW buffer layers are the same as the HWCVD i layers, but the SC was kept at 5%. The solar cell area is 1×1 cm^2. If not otherwise stated, all solar cells are $\sim$1 μm thick and with Ag back contacts. The current-voltage (J-V) parameters under AM1.5 illumination were measured at 25 °C. Raman scattering measurements with 488 nm excitation were performed on the solar cells after the removal of the n layers to semiquantitatively evaluate the crystalline volume fraction (I_C^{RS}).[15] Structure evolution along the growth axis was investigated by a "depth profile" method, in which Raman scattering measurements were carried out on the craters with different depths etched into the i layers. De-

[a)]Also at: the Institute of Photoelectronics, Nankai University, Tianjin 300071, People's Republic of China.
[b)]Author to whom correspondence should be addressed; electronic mail: y.mai@fz-juelich.de

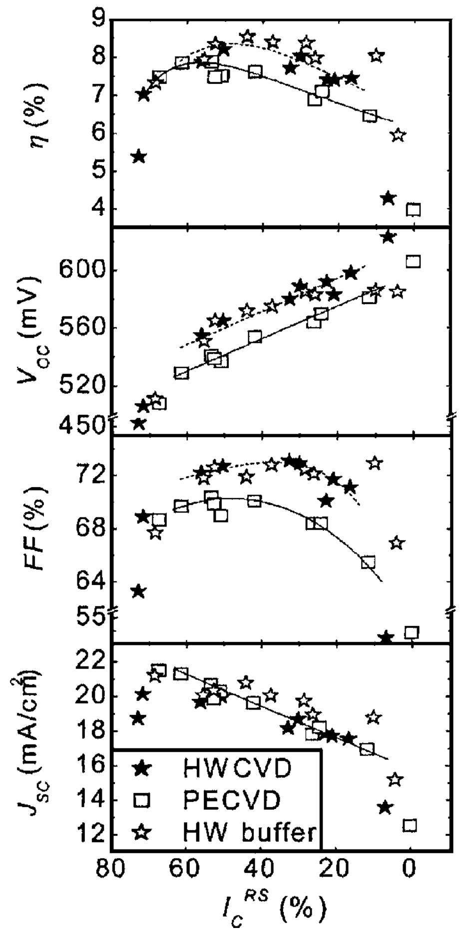

FIG. 1. *J-V* characteristics, η, V_{OC}, FF, and J_{SC}, of μc-Si:H solar cells with i layers deposited by PECVD or HWCVD, plotted as a function of I_C^{RS}. A 100 nm thick HW p/i buffer layer in PECVD solar cells nearly eliminates the differences between the PECVD and HWCVD solar cells. Lines are guides for the eye.

tails of this method are described elsewhere.[16]

The *J-V* parameters, i.e. efficiency (η), V_{OC}, FF, and short circuit current density (J_{SC}), of the three series are plotted in Fig. 1 as a function of the i layer I_C^{RS}. In good agreement with previous results,[1,2] the efficiency of the PECVD series reaches the maximum at ~540 mV and decreases sharply as V_{OC} increases further, while HWCVD solar cells with high V_{OC} up to 598 mV still maintain a high performance. High efficiencies of ~8% are obtained for the 1 μm thick optimum solar cells in both series, indicating that both techniques are capable of providing high-quality material. In a wide range of I_C^{RS} between 60% and 10%, both series show similar J_{SC} at similar I_C^{RS}. The decrease of J_{SC} in this region can be attributed to the low absorption coefficient of the long-wavelength light in the increasing amorphous phase in the i layer. The V_{OC} depends critically on the i layer crystallinity and increases with decreasing I_C^{RS}. An important observation is that the HWCVD series shows 20 mV higher V_{OC} values than the PECVD samples in the I_C^{RS} region between 60% and 10%. In addition, HWCVD solar cells show higher FF (~3% abs.) in this region, and a HWCVD sample with low I_C^{RS} of 17% still maintains high FF over 71%, indicating a remarkable difference between the two series.

Inserting a 100 nm thick intrinsic HWCVD buffer layer between the p and i layer of the PECVD solar cells nearly eliminates these differences. The series with HW buffers shows very similar V_{OC} and *FF* as the HWCVD cells at the same I_C^{RS}, although 900 nm of the bulk i layers were deposited by PECVD. A solar cell with a low I_C^{RS} of 28% and V_{OC} of 585 mV still exhibits surprisingly high performance (η:8.37%, FF: 72.4 %), which up to now could only be obtained with i layers prepared entirely by HWCVD. Furthermore, we also found that varying the buffer layer structure composition to some extent and reducing the thickness down to 5 nm makes no visible difference in the solar cell performance (not shown in this paper).

Applying such HW buffers to the PECVD solar cells (using the lplP process for the bulk i layer) with a thicker i layer and highly reflective ZnO/Ag back contact leads to a high efficiency of 9.6% with a V_{OC} of 572 mV for a single junction μc-Si:H solar cell, which is comparable to the HWCVD results in Ref. 2. Depositing the bulk i layer under hphP conditions with a R_D of 11 Å/s,[3] we achieved an even higher efficiency of 10.3% for a 1.6 μm thick cell with a V_{OC} of 568 mV.

A previous comparison between the PECVD and HWCVD solar cells at the same I_C^{RS} revealed that they are very similar in the bulk i layer quality, and the differences between them can be attributed to the more effective carrier extraction at the p/i interface in the HWCVD cells.[13] Raman scattering experiments conducted on these three solar cell series presented in this paper show that the buffer layer has only little influence on the bulk layer crystallinity, which is mainly determined by the *SC* used for the bulk layer preparation. Furthermore, a positive effect of the HW-buffer layer for facilitating nucleation and thus more homogeneous growth in the depth direction in the i layer was not conclusively supported by the Raman structure depth profiles, in which the I_C^{RS} differences between the top and the bottom of the i layer are found typically within 10% in all PECVD, HWCVD, and HW-buffer solar cells. On the other hand, the influence of the HW buffer layer on the carrier extraction at the p/i interface was confirmed by a measurement of the *J-V* parameters under blue light illumination. As the short-wavelength light will be nearly fully absorbed in the i layer close to the p/i interface, the solar cell response in this wavelength region can be considered as a criteria for the p/i interface quality. Note that p layers are the same in all solar cells presented in this paper. Figure 2 shows the FF and J_{SC} data of the solar cell series (the same as in Fig. 1) under blue light illumination (AM1.5 spectrum with a bandpass filter, bg7, centered at 480 nm). Higher blue light FF and J_{SC} can be observed in HWCVD solar cells in the region with I_C^{RS} $<60\%$, where they show higher V_{OC} and FF than the PECVD samples at the same I_C^{RS}, indicating better extraction efficiency for the carriers generated at the p/i interface. In the same I_C^{RS} region, the incorporation of the HW buffer layer in PECVD cells leads to an improvement of blue light J_{SC} and FF. Down to I_C^{RS} values of about 10%, where poor blue light response is found in PECVD cells, high FF of 73.4%, and high J_{SC} are obtained with the use of a HW buffer.

An incubation layer with a high content of amorphous phase at the p/i interface was previously regarded as a reason for deteriorated p/i interface quality.[4,16] This assumption is not supported by the Raman structure depth profiles in this research, in which the I_C^{RS} differences between the top and the bottom of the i layer are found typically within 10% in

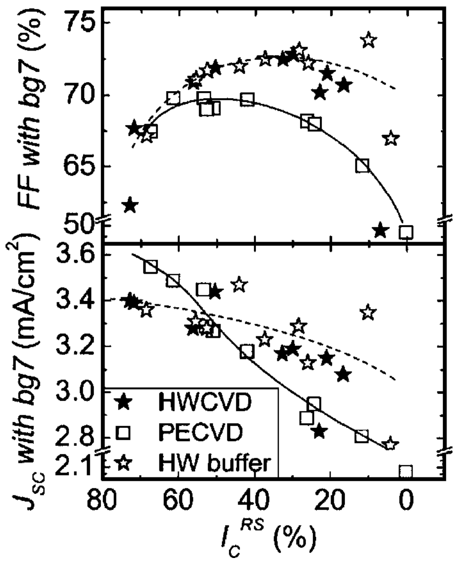

FIG. 2. FF and J_{SC} of three solar cell series (the same as in Fig. 1) under the illumination of AM1.5 through a short-wavelength bandpass filter (bg7). Together with the V_{OC} and FF improvement in the PECVD solar cells with I_C^{RS} between 60% and 10%, a better short-wavelength response due to the application of HW p/i buffer layers was observed. Lines are guides for the eye.

all solar cells. An alternative plausible explanation for the more effective carrier extraction at the p/i interface in HW-buffer solar cells might be the absence of ion bombardment damage in the HWCVD process, which was already found beneficial in the SiN_x deposition for integrated circuit application.[17,18]

In summary, three solar cell series with different i layers deposited either by PECVD or HWCVD were compared. A better p/i interface in the HWCVD solar cells is regarded as the reason for higher V_{OC}, FF, and enhanced blue light response. Using a HWCVD p/i buffer layer in the PECVD cells can eliminate these differences. With this buffer layer concept, a high efficiency of 10.3% at high V_{OC} of ~570 mV was obtained for a μc-Si:H single junction solar cell in which the PECVD i layer was deposited at a high R_D of 11 Å/s.

The authors thank T. Brammer and C. Ross for the helpful discussion and F. Birmans, M. Hülsbeck, A. Lambertz, S. Michel, G. Schöpe, H. Siekmann, J. Wolff, and C. Zahren for their technical assistance.

[1] O. Vetterl, F. Finger, R. Carius, P. Hapke, L. Houben, O. Kluth, A. Lambertz, A. Mück, B. Rech, and H. Wagner, Sol. Energy Mater. Sol. Cells **62**, 97 (2000).

[2] S. Klein, F. Finger, R. Carius, B. Rech, L. Houben, M. Luysberg, and M. Stutzmann, Mater. Res. Soc. Symp. Proc. **715**, A26.2 (2002).

[3] Y. Mai, S. Klein, X. Geng, and F. Finger, Appl. Phys. Lett. **85**, 2839 (2004).

[4] H. Stiebig, T. Brammer, J. Zimmer, O. Vetterl, and H. Wagner, J. Non-Cryst. Solids **266–269**, 1104 (2000).

[5] F. Finger, S. Klein, T. Dylla, A. L. Baia Neto, O. Vetterl, and R. Carius, Mater. Res. Soc. Symp. Proc. **715**, A16.3 (2002).

[6] H. Keppner, J. Meier, P. Torres, D. Fischer, and A. Shah, Appl. Phys. A: Mater. Sci. Process. **69**, 169 (1999).

[7] M. Kondo and A. Matsuda, Thin Solid Films **457**, 97 (2004).

[8] H. Matsumura, Jpn. J. Appl. Phys., Part 2 **30**, L1522 (1991).

[9] A. H. Mahan, J. Carapella, B. P. Nelson, R. S. Crandall, and I. Balberg, J. Appl. Phys. **69**, 6728 (1991).

[10] J. K. Rath, A. J. Hardeman, C. H. M. van der Werf, P. A. T. T. van Veenendaal, M. Y. S. Rusche, and R. E. I. Schropp, Thin Solid Films **430**, 67 (2003).

[11] M. Kupich, D. Grunsky, P. Kumar, and B. Schröder, Sol. Energy Mater. Sol. Cells **81**, 141 (2004).

[12] P. Alpuim, V. Chu, and J. P. Conde, J. Appl. Phys. **86**, 3812 (1999).

[13] Y. Mai, S. Klein, X. Geng, M. Hülsbeck, R. Carius, and F. Finger, Thin Solid Films (to be published).

[14] O. Kluth, B. Rech, L. Houben, S. Wieder, G. Schöpe, C. Beneking, H. Wagner, A. Löffl, and H. W. Schock, Thin Solid Films **351**, 247 (1999).

[15] L. Houben, M. Luysberg, P. Hapke, R. Carius, F. Finger, and H. Wagner, Philos. Mag. A **77**, 1447 (1998).

[16] Y. Mai, S. Klein, R. Carius, J. Wolff, A. Lambertz, F. Finger, and X. Geng, J. Appl. Phys. **97**, 114913 (2005).

[17] H. Matsumura, Jpn. J. Appl. Phys., Part 1 **28**, 2157 (1989).

[18] B. Stannowski, J. K. Rath, and R. E. I. Schropp, J. Appl. Phys. **93**, 2618 (2003).