Solar Energy Materials & Solar Cells 95 (2011) 2576–2582

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Reduction of optical losses in colored solar cells with multilayer antireflection coatings

J.H. Selj *, T.T. Mongstad, R. Søndenå, E.S. Marstein

Department of Solar Energy, Institute for Energy Technology (IFE), P.O. Box 40, NO-2027 Kjeller, Norway

ARTICLE INFO

Article history:
Received 23 September 2010
Accepted 4 March 2011
Available online 4 May 2011

Keywords:
Multilayer antireflection coatings
Porous silicon
Solar cells
Design
Building-integrated PV (BIPV)

ABSTRACT

Solar modules are becoming an everyday presence in several countries. So far, the installation of such modules has been performed without esthetic concerns, typical locations being rooftops or solar power plants. Building-integrated photovoltaic (BIPV) systems represent an interesting, alternative approach for increasing the available area for electricity production and potentially for further reducing the cost of solar electricity. In BIPV, the visual impression of a solar module becomes important, including its color. The color of a solar module is determined by the color of the cells in the module, which is given by the antireflection coating (ARC). The ARC is a thin film structure that significantly increases the amount of current produced by and, hence, the efficiency of a solar cell. The deposition of silicon nitride single layer ARCs with a dark blue color is the most common process in the industry today and plasma enhanced chemical vapor deposition (PECVD) is mostly used for this purpose. However, access to efficient, but differently colored solar cells are important for the further development of BIPV. In this paper, the impact of varying the color of an ARC upon the optical characteristics and efficiency of a solar cell is investigated. The overall transmittance and reflectance of a set of differently colored single layer ARCs are compared with multilayered silicon nitride ARCs, all made using PECVD. These are again compared with porous silicon ARCs fabricated using an electrochemical process allowing for the rapid and simple manufacture of ARC structures with many tens of layers. In addition to a comparison of the optical characteristics of such solar cells, the effect of using colored ARCs on solar cell efficiency is quantified using the solar cell modeling tool PC1D. This work shows that the use of multilayer ARC structures can allow solar cells with a range of different colors throughout the visual spectrum to retain very high efficiencies.

1. Introduction

The use of solar cells for electricity production has increased rapidly for more than a full decade. As a result, solar energy systems are becoming an increasingly visible part of everyday life in several countries. Today, the majority of solar cells are currently installed with little regard to esthetics, in locations such as rooftops or solar power plants. Building-integrated photovoltaic (BIPV) systems represent an interesting, alternative approach for increasing the available area for electricity production and potentially for further reducing the cost of solar electricity [1, Chapter 22]. However, BIPV does not represent a large share of the market today. One factor is that BIPV elements are in part hampered by a limited choice of esthetic variation. In one survey, more than 85% of architects stated that esthetic concerns would allow for the installation of solar energy systems with reduced efficiency [2]. One suggested requirement for a 'well integrated' solar energy system is that it results in a good composition of colors and materials [1, Chapter 22]. Clearly, access to efficient solar modules with a range of colors is desirable.

Deposition of antireflection coatings (ARCs) at the front of the solar cell is a standard procedure in silicon solar cell fabrication. The ARC improves the photon collection of the cell by reducing the high reflectance of a bare Si wafer ($>30\%$) to around 10%. The reflectance is further reduced with standard texturing. The most commonly used ARC in industry today is a thin single layer of amorphous, hydrogenated silicon nitride (a-SiN_x:H, henceforth shortened to SiN_x) deposited by plasma enhanced chemical vapor deposition (PECVD). In addition to improving the efficiency, the ARC also determines the color of the solar cell.

In principle, there is much room for modifying the appearance of a solar cell by the variation of the ARC. First, by simply varying the thickness of the silicon nitride ARC covering the solar cell, a range of colors can be obtained [3]. However, in the case of single layer ARCs of today, this leads to a significant reduction in the light transmitted into the solar cell [4]. A second option, therefore,

* Corresponding author. Tel.: +47 63 80 64 29; fax: +47 63 81 29 05.
E-mail address: josefine.selj@ife.no (J.H. Selj).

0927-0248/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.solmat.2011.03.005

is the use of multilayer ARCs to obtain an increased selection of colors, a benefit which can be combined with reduced optical losses. The deposition of stacks with large numbers of layers is a challenge, at least in a high-throughput, low cost production environment. However, if the relative efficiency gain of differently colored solar cells is sufficiently increased through the use of one slightly more complex processing step, this can potentially justify the use of multilayer coatings in solar cells for BIPV.

In this paper, both single layer SiN_x ARCs and multilayered ARCs consisting of SiN_x and silicon oxide (SiO_x:H, henceforth shortened to SiO_x) were produced by plasma enhanced chemical vapor deposition (PECVD). For simple processing, only three-layer ARCs requiring relatively short process times are investigated in this paper. The two deposited materials were obtained by using standardized deposition parameters. Modifications of the deposition parameters can give room for further modulations of the optical response.

A third and very promising approach towards the rapid and simple manufacture of multilayer ARCs with very high numbers of layers is electrochemical etching of nanoporous silicon (PS) [5]. By varying the current density during etching the compositional fraction of Si and air can be controlled. The optical properties of PS are closely related to the porosity of the material. This results in a unique opportunity to tailor refractive index profiles and create complex broadband ARCs. Single and double layer PS ARCs have been incorporated into efficient silicon solar cells by several groups [6–10], but is currently not used in industrial solar cell production.

In this paper, the obtainable colors and transmission losses resulting from the use of single and multilayer films deposited by PECVD are compared to those of PS ARCs. In addition to a comparison of the optical characteristics of such solar cells, the effect of using colored ARCs on solar cell efficiency is quantified using the solar cell modeling tool PC1D [11].

2. Material and methods

Dielectric films and nanoporous silicon films optimized for antireflection were synthesized and characterized in this work. A PlasmaLab 133 reactor from Oxford Systems was used to deposit single or three-layer ARC stacks. The single layer ARCs were made from conventional amorphous, hydrogenated silicon nitride (SiN_x) with a refractive index (n_{SiN}) of ~ 1.95. The triple-layer ARCs were stacks of SiN_x and SiO_x (n_{SiO} ~ 1.45) in the following order: $SiN_x/SiO_x/SiN_x$. SiN_x was deposited at 400° using a gas-mix consisting of N_2, NH_3, and SiH_4, while SiO_2 was deposited at 300° using N_2, N_2O, and SiH_4.

Another set of samples was made by electrochemical synthesis of PS films. For these experiments, a double cell electrochemical etching system, PSB Plus 4, from advanced micromaching tools (AMMT) was used. The substrates used were boron doped monocrystalline silicon wafers, 300−350 μm thick, one side polished, with a (1 0 0) orientation. A special purpose potensiostat, PS2 from AMMT, allowed programming of current density profiles with a time resolution of 50 ms.

Selection of colors and modeling of the performance of the structures were performed prior to sample preparation. For the single and triple-layer stacks, the modeling was performed using the software package MacLeod from Thin Films Center Inc. [12]. For the PS layers, the ellipsometric software WVASE32 from Woollam was used.

Prior to the deposition of the films of SiN_x and SiO_x, the thickness and deposition rate of the separate films were assessed by ellipsometry. The ellipsometer used was a variable angle spectroscopic ellipsometer (VASE) from Woollam. For PS, careful mapping of the relation between current density, porosity and etch rate was performed on single layers prior to etching complex structures.

Table 1
Solar cell parameters used during PC1D simulations.

Parameter	Value
Base contact	0.015 Ω
Internal conductor	0.3 S
Internal optical reflection	80% (specular)
Thickness	270 μm
Diffusion: sheet res./peak dop./depth factor	50Ω sq/1.9×10^{20} cm^{-3}/0.25
Bulk lifetime	50 μs
Front surface recombination	50 000 cm/s
Rear surface recombination	1000 cm/s

After the two different ARC structures were fabricated, their optical and structural properties were characterized using ellipsometry and reflectance measurements. Reflectance measurements were carried out using an integrated sphere spectral response setup. From the measured reflectance spectra color coordinates which represent a numerical rendering of the color of the ARC can be calculated. Here the International Commission on Illumination (CIE) *xy* color coordinates are used. The coordinates are obtained by combining the information from the calibrated reflectance spectra in the wavelength range 400–830 nm with the CIE color matching functions which are the numerical description of the chromatic response of an observer [13,14].

In addition to optical characterization, the impact of the resulting transmission variations upon solar cell efficiency was determined by device modeling. The resulting modifications to the short circuit current density (J_{sc}), and efficiency were obtained by using the software PC1D [11]. The transmittance spectra used as input in the PC1D modeling is found by combining absorptance spectra obtained from ellipsometry with measured reflectance spectra. The main characteristics of the solar cell model are described in Table 1.

It should be mentioned that the ARCs described herein are optimized for use in an air ambient. Practical solar cells will be encapsulated in a polymer (EVA) and protected by glass. However, using encapsulated structures with EVA and glass complicates the characterization of the ARC structure and such encapsulation is not necessary in order to illustrate the procedures and the possibilities of the investigated ARCs. The methods applied in this work can easily be applied to design ARCs for use in a conventional, laminated solar module configuration [5] without sacrificing color flexibility or low reflectance.

3. Theory/calculation

3.1. Optics

For the single and triple-layer structures fabricated with PECVD, MacLeod was used for determining suitable thicknesses of the layers. For the modeling, layers with a refractive index of 1.95 (SiN_x) and 1.45 (SiO_x) were used. For simplicity, the layers were assumed to be non-absorbing during the modeling. In order to obtain clear colors while maintaining low reflection, a target spectrum with high reflectance in a selected wavelength range and very low reflectance for the remaining, relevant part of the solar spectrum, was defined. The highly reflective wavelength range is chosen according to the desired color of the film.

The layer thicknesses best suited to reproduce the target spectrum are the direct outcome of the fitting procedure.

By using PS, multiple layers with different refractive indices can be etched in one single process-step. Both the thickness and the refractive index can then be varied to obtain the desired reflectance. Modeling of the optimal PS structure is complicated by the need of a relation between the porosity and the refractive index. This challenge is met by using the ellipsometric software tool WVASE32 for modeling. The software is usually used to model the physical properties of materials based on information from optical data. Hence, approximations providing the necessary bridge between refractive index and compositional fractions are easily accessible. Effective medium models where the refractive index of the resulting structure is a mix of the refractive indices of air and silicon, are commonly used to model PS [15]. In this work it is the Bruggeman effective medium approximation [16] that is utilized. The optical constants of Si are taken from [17]. The flexibility in the modulation of the reflectance spectra generally increases with increasing number of PS layers, but for such thin structures as those presented here, the improvement quickly saturates. Since the total etching time of all PS multilayers prepared in this work is less than 10 s, there are also practical limits on the number of steps which can be implemented in the actual ARC. The smallest time interval permitted by the potensiostat is 50 ms. As a result, a compositional model of PS with 36 layers is chosen to accommodate both practical and optimal considerations. The structure consists of eight nodes, with five steps in the first seven nodes and the last node constituting the final step. The Levenberg–Marquet minimization routine is used to find the porosity profile which best corresponds to the predefined reflectance. Absorption is not taken into account in the optimization procedure, but an upper limit on thickness is set to reduce unwanted absorption in the ARC.

For both types of ARCs, absorption is accounted for the final evaluation of their performance calculated in PC1D.

3.2. Solar cell modeling using PC1D

Although a comparison of the overall transmittance over the relevant wavelength region gives a good first impression of the impact of the different ARCs upon efficiency, the quantum

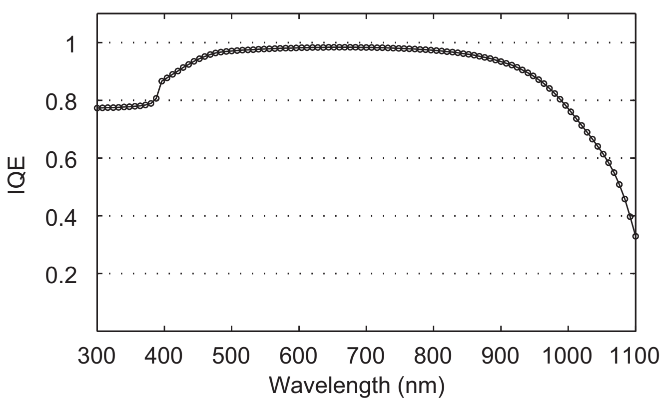

Fig. 1. The internal quantum efficiency of the solar cell model used for PC1D simulations.

Table 2
Reflectance, absorptance and transmittance through the ARCs, weighted by the reference solar spectrum [18]. CIE color coordinates for the 10° field of view provide numerical values for the color rendering.

Sample	CIE coord. (x,y)	Refl.	Abs.	Trans.
Single layer SiN – green	0.353, 0.430	0.115	0.035	0.837
Single layer SiN – red	0.161, 0.164	0.094	0.019	0.874
Single layer SiN – blue	0.181, 0.184	0.090	0.028	0.869
Dielectric stack – green	0.386, 0.442	0.175	0.048	0.777
Dielectric stack – red	0.331, 0.233	0.245	0.070	0.685
Dielectric stack – blue	0.224, 0.244	0.143	0.014	0.843
PS multilayer – green	0.339, 0.425	0.074	0.075	0.859
PS multilayer – red	0.351, 0.283	0.042	0.064	0.893
PS multilayer – purple	0.221, 0.188	0.030	0.064	0.907
PS multilayer – orange	0.384, 0.408	0.022	0.059	0.918

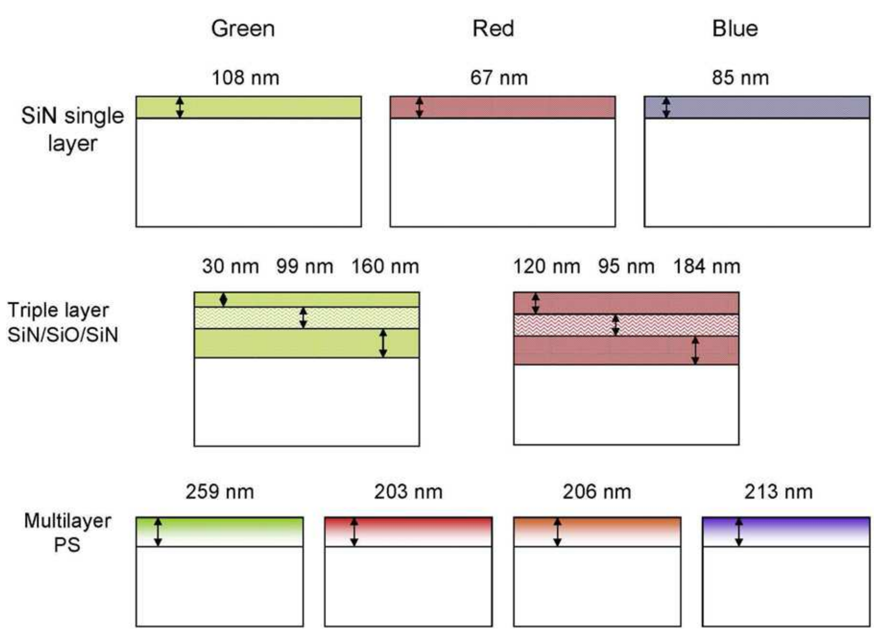

Fig. 2. An overview over the fabricated structures. The thicknesses are determined by spectroscopic ellipsometry. The 'red' single layer ARC is only intended to be red, the layer in fact appears blue.

efficiency of a solar cell also depends strongly on the wavelength. In order to enable a better assessment of the effect of introducing colored ARCs on solar cells, PC1D was used as a modeling tool. The basis for the modeling was the solar cell model shown in Table 1. The resulting spectral internal quantum efficiency, IQE (λ), of this solar cell model is shown in Fig. 1. The solar cell model results in fairly representative solar cell characteristics, with well-known reductions of IQE (λ) both towards short and long wavelengths. For all of ARC structures, experimentally determined transmittance spectra were used as input to the modeling. For simplicity and a more direct comparison with the results from the optical characterization, the cells were assumed to be without any surface texture. Also, shading losses were neglected. The reflection of long wavelength light from the metallized rear surface of the solar cell is taken into account by adding a rear side mirror with a reflectance of 80%.

Table 3
Simulated efficiencies obtained when each ARC is used on a standardized solar cell. Simulated values for short circuit current density (J_{sc}) and open circuit voltage (V_{oc}) are also shown.

Sample	Efficiency	J_{sc}	V_{oc}	J_{sc}/J_{sc} (*black*)(%)
"Black"[a]	19.8	38.5	620.1	100.0
Single layer SiN – green	16.6	32.5	615.8	84.4
Single layer SiN – red	17.6	34.5	617.4	89.6
Single layer SiN – blue	17.5	34.1	617.1	88.6
Dielectric stack – green	15.2	29.8	613.5	77.4
Dielectric stack – red	13.0	25.7	609.7	66.8
Dielectric stack – blue	16.6	32.5	615.7	84.4
PS multilayer – green	16.9	33.0	616.2	85.7
PS multilayer – red	17.5	34.3	617.2	89.0
PS multilayer – purple	17.8	34.8	617.7	90.4
PS multilayer – orange	18.1	35.4	618.0	91.9

[a] "Black" refers to perfect transmission through the ARC; no reflection, no absorption.

4. Results and discussion

An overview over the fabricated ARC structures is given in Fig. 2. The first row shows the thicknesses and colors of the single SiN_x layers, the second row illustrates the structure and the thicknesses of the three-layer dielectric stacks, and the third row shows the thicknesses of the four PS stacks. All thicknesses are determined by spectroscopic ellipsometry. The effective, weighted reflectance, absorptance and transmittance of each of the structures, in the wavelength range 300–1100 nm, is given in Table 2. The solar spectrum used for weighting the number of incoming photons of different wavelengths is the standardized 1.5AM terrestrial reference spectrum [18] adopted by the American Society for Testing and Materials (ASTM). Pictures and reflectance spectra of each of these ARCs are shown in Section 4.1. An evaluation of the performance of the ARC structures when integrated in a solar cell is performed in

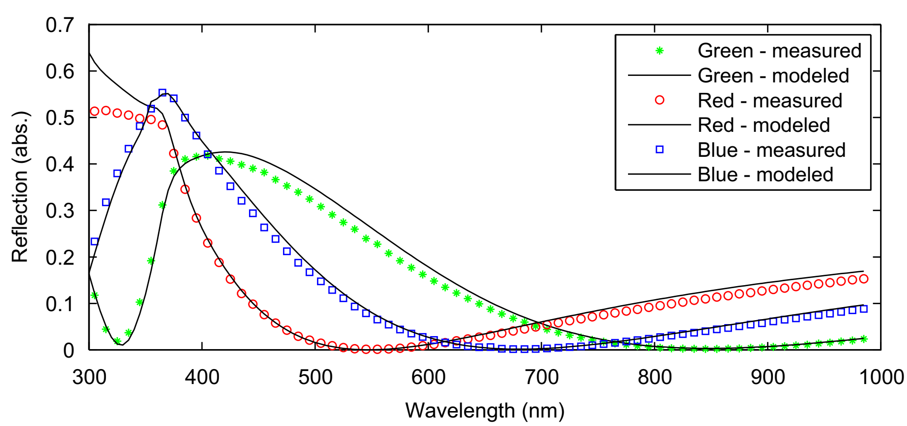

Fig. 3. Reflectance spectra of the single SiN_x layers designed to appear green, red, and blue, respectively. The curve 'measured' refers to the measured spectra and 'modeled' refers to the spectra extracted from the best fit ellipsometric model of the structures. Note that the single SiN_x layer intended to be red is in reality blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

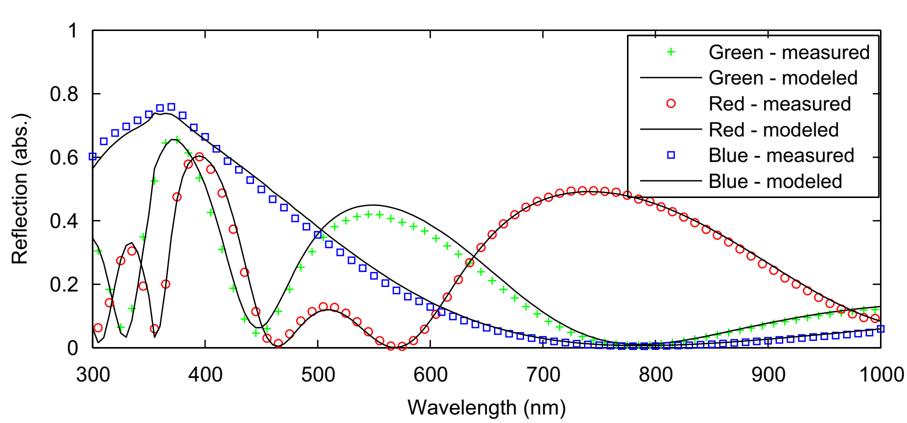

Fig. 4. Reflectance spectra of the green, red, and blue triple-layer dielectric stacks. The curve 'measured' refers to the measured spectra and 'modeled' refers to the spectra extracted from the best fit ellipsometric model of the structures. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

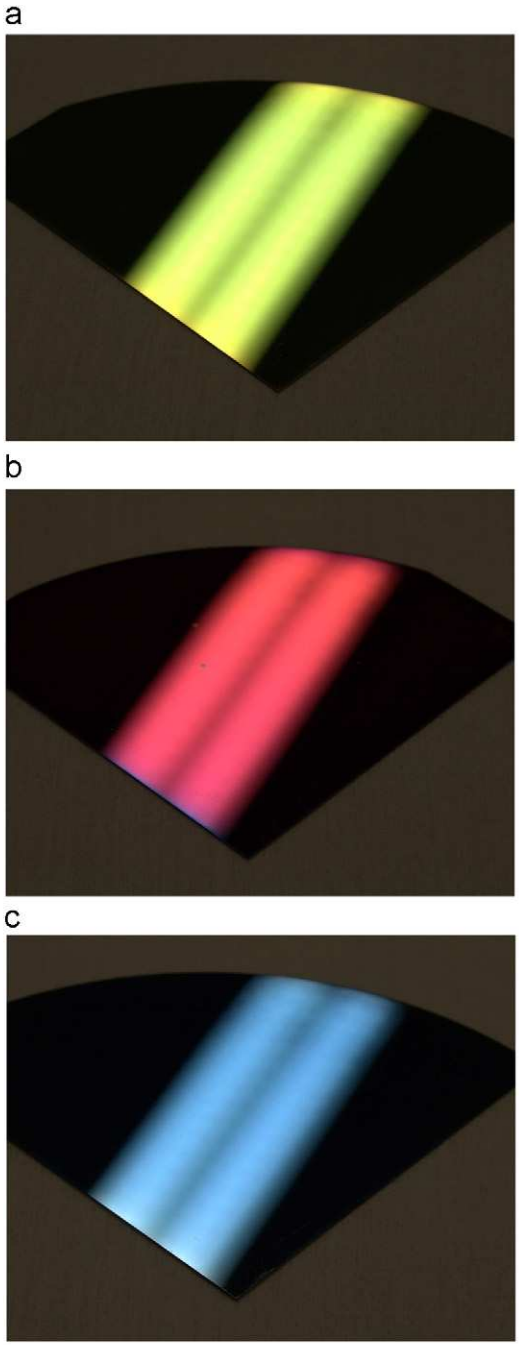

Fig. 5. Photographs of the colored triple-layer dielectric stack ARCs. The samples are illuminated by a rectangular white fluorescent lamp which can be discerned in the reflection from the sample. (a) Green dielectric stack; (b) red dielectric stack; (c) blue dielectric stack.

PC1D. The efficiencies resulting from each of the ARC structures is summarized in Table 3.

4.1. Reflectance

The reflectance spectra of the fabricated structures are shown in Figs. 3, 4 and 6. The measured reflectance is labeled 'measured' and the reflectance generated from the best fit ellipsometric model is labeled 'modeled'. Note that it is the thickness and optical constants of the layers that are directly modeled by ellipsometry. The reflectance is calculated from the best fit model. The excellent fit between 'measured' and 'modeled' is therefore a strong support of the validity and accuracy of the ellipsometric models employed. The reflectance measurements are performed in the wavelength range 300–1000 nm, due to influence from backside reflection in the wafer in the range 1000–1100 nm. In this wavelength range, modeled data is used in calculations of reflectance in Table 2. Although absorption was not taken into account during the optimization procedure, it should be known in order to evaluate the optical performance of the fabricated structures. The ellipsometric models can be used to obtain the absorptance for each ARC. For these calculations a wavelength range of 300–1100 nm is used. The transmitted spectra, used as input for efficiency simulations in PC1D, are obtained from these absorptance and reflectance spectra. The integrated reflectance, absorptance and transmittance given in Table 2 are weighted by the reference solar spectrum [18] in the wavelength range 300–1100 nm.

4.1.1. SiN and dielectric stack ARCs

Fig. 3 shows the reflectance spectra achieved with single layer SiN_x optimized for green, red and blue reflectance spectra, respectively. The integrated reflectances are low, but the available color range is limited as the layer thickness is the only variable in these films. The reflectance spectra have a single point of zero-reflection. The film that was designed to be red in fact appears blue when it is fabricated. This illustrates the difficulty of achieving different colors with only one SiN_x layer. Ellipsometric modeling of these simple structures is straight forward and the accordance between measured and modeled values is excellent.

Fig. 4 shows the reflectance spectrum achieved with triple-layer dielectric stacks of $SiN_x/SiO_x/SiN_x$ optimized for green, red and blue reflectance spectra. The possibility of tailoring the color of the reflectance spectra is significantly improved, at the expense of an increased reflectance.

Ellipsometric modeling is carried out by using optical constants obtained from single layer SiN_x made under the same deposition parameters. Optical constants for the SiO_x are approximated by tabulated values for SiO_2 taken from Palik et al. [19]. The thicknesses of the three layers are fitted. Again the accordance between measured and modeled data is very good. Fig. 5 shows the colors of the triple-layer $SiN_x/SiO_x/SiN_x$ ARCs corresponding to the reflectance spectra in Fig. 4. All the SiN_x reflectance spectra have a small systematic wavelength shift compared to the designed stack. This is due to a small thickness deviation. Further optimization of the deposition parameters could improve the accuracy with which the designed spectra are reproduced.

4.1.2. Multilayer nanoporous silicon ARCs

Fig. 6 shows the measured ('measured') and ellipsometric model generated ('modeled') reflectance spectra of the fabricated colored PS ARCs. Green (a), red (b), purple (c), and orange (d) PS ARCs are demonstrated. Fig. 7 shows pictures of the PS ARCs corresponding to the reflectance spectra in Fig. 6. Control over both thickness and refractive index results in a large freedom of tailoring the reflectance spectra of the films. The layers can then be optimized for low reflectance in addition to specific color. As seen in Table 2, the integrated reflectance of the PS ARCs are extremely low. Especially as no texturing is performed prior to electrochemical etching.

4.2. Solar cell efficiencies

The efficiency, short circuit current density, and open circuit voltage of the standardized solar cell with the different colored ARCs are shown in Table 3. Green, red, blue, purple, and orange colored ARCs are produced that result in simulated efficiencies $> 16.9\%$. PS ARCs provide the highest efficiencies for all colors,

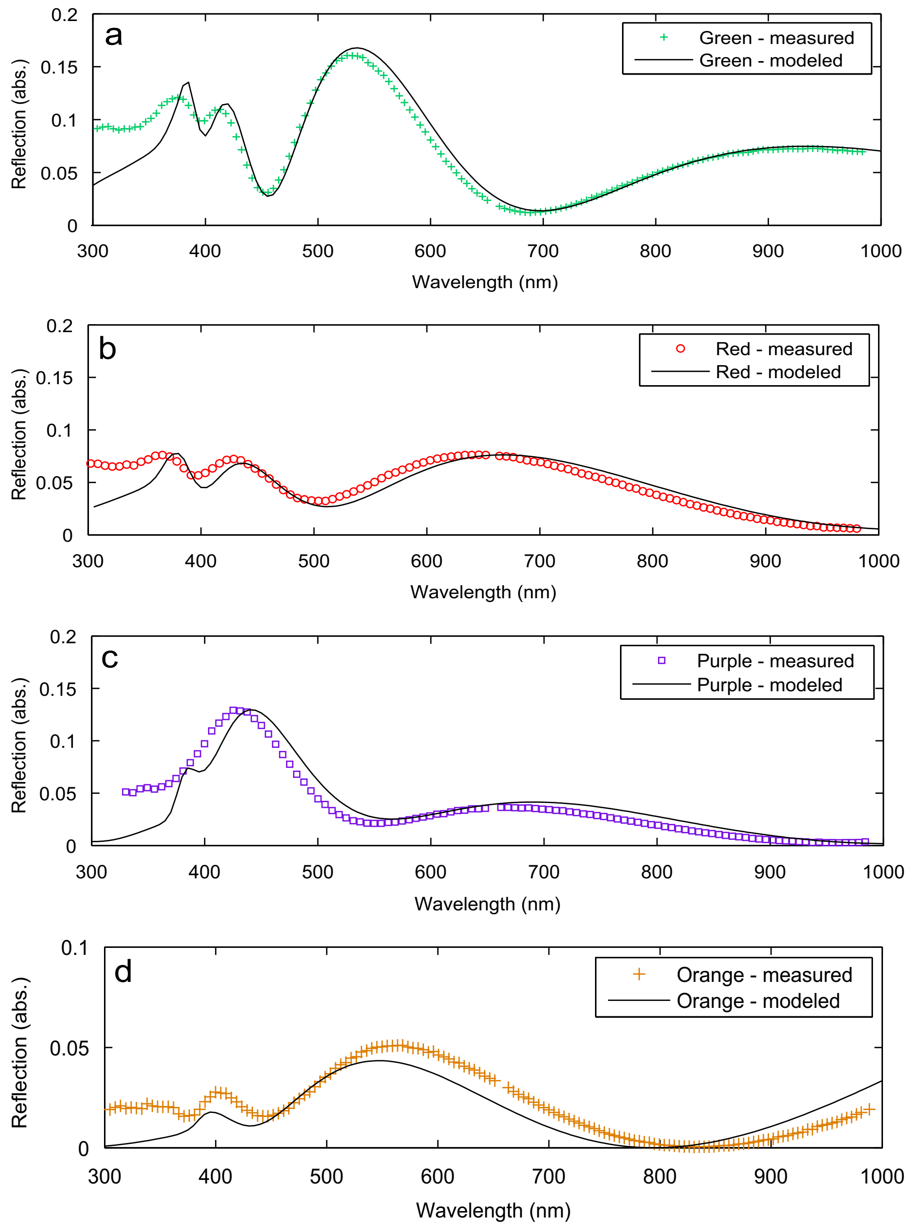

Fig. 6. Reflectance from colored PS ARCs. The measured reflectance ('measured') is shown together with the reflectance generated from the optical constants in the best fit ellipsometry model ('modeled').

but for blue and green ARCs the lead is marginal. For blue ARCs there is no gain in efficiency by going from single layer SiN to a triple-layer dielectric stack, but more flexibility is provided with respect to tailoring the tint of the color. For the green ARCs, a modest efficiency improvement is obtained by using a triple-layer dielectric stack compared to a single layer SiN_x. In the red part of the spectrum, PS ARCs yield exceptionally low reflectance, resulting in significantly higher efficiencies than the triple-layer dielectric stacks. It seems to be difficult to produce clear, red colors with a single layer SiN_x ARC.

In order to investigate the potential of these techniques for fabrication of colored ARCs, a selection of target colors were made. Optimization with respect to thickness and possible adjustments in the target reflectance spectra during modeling may give further improvements in efficiency for both the dielectric stacks and the multilayer PS. For the PS layers, improved control over formation parameters can enhance efficiencies due to closer match between designed and fabricated structures. For SiN_x exciting possibilities to change the refractive index during deposition are emerging. This could increase the flexibility and enhance the efficiencies of colored SiN_x ARCs.

5. Conclusions

We have here showed that the ARC of solar cells can be tailored to give clear colors while retaining high efficiencies. Although the reflectance from single layer SiN_x ARCs is generally low, the colors available by simple thickness variations are limited. Using triple-layer SiN_x ARCs, a broader range of colors can be achieved, at the expense of a significant increase in reflectance. This approach represents a relatively small modification to the current production process flow for wafer-based Si solar cells and can be a viable, short term route to the production of differently colored solar modules for use in BIPV and other applications where esthetic concerns are of importance.

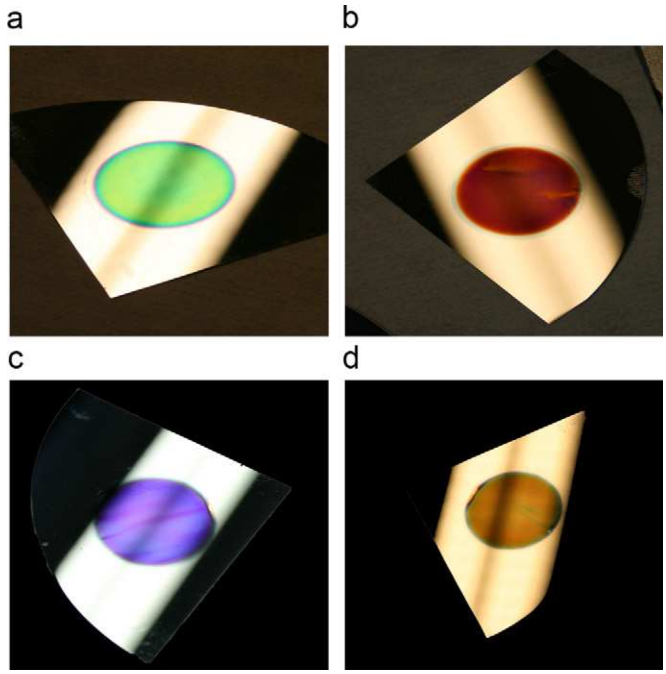

Fig. 7. Appearance of the colored multilayered PS ARCs. The circle with an area of $\sim 4\ cm^2$ is the area where PS has been etched. The reflection from a rectangular white fluorescent lamp above the sample is visible in the photograph. (a) Green, PS multilayer stack; (b) Red, PS multilayer stack; (c) Purple, PS multilayer stack; (d) Orange, PS multilayer stack.

By electrochemical etching of the Si wafer, colored ARCs with lower reflectance than conventional, single layer SiN_x ARCs can be produced. Colored solar cells able to absorb in excess of 90% of the incoming light is shown to be accessible with these structures. However, important issues such as passivation and process-integration need further improvement before PS ARCs can be implemented in industrial solar cell production [20].

Acknowledgments

This work has been funded by the Research Council of Norway through the project "Thin and highly efficient silicon-based solar cells incorporating nanostructures," NFR Project No. 181884/S10.

References

[1] T. Reijenga, PV in architecture, in: E. Luque, S. Hegedus (Eds.), Handbook of Photovoltaic Science and Engineering, John Wiley & Sons, 2003, pp. 1005–1042.
[2] W. Weiss, I. Stadler, Faade integration, a new and promising opportunity for thermal solar collectors, in: Proceedings of the Industry Workshop of the IEA Solar Heating and Cooling Programme (2001).
[3] H.A. MacLeod, Thin Film Optical Filters (pp. 5–40), Institute of Physics Publishing, 2001.
[4] R. Tölle, R. Bruton, T. Noble, R. Schneider, A. Janka, J.-P. Costard, H. Claus, J. Radike, M. Summhammer, J. Hilcox, D. Aceves, O. Anzizu, O. Koch, W. Tobias, I. Luque, The production of aesthetically pleasing module prototypes within the "bimode" – project, in: Proceedings of the 16th European Photovoltaic Solar Energy Conference (2000), pp. 1957–1959.
[5] J.H. Selj, A. Thøgersen, S.E. Foss, E.S. Marstein, Optimization of multilayer porous silicon antireflection coatings for silicon solar cells, Journal of Applied Physics 107 (2010) 074904-1–074904-10.
[6] S. Strehlke, D. Sarti, A. Krotkus, K. Grigoras, C. Levy-Clement, The porous silicon emitter concept applied to multicrystalline silicon solar cells, Thin Solid Films 297 (1997) 291–295.
[7] L. Schirone, G. Sotgiu, F.P. Califano, Chemically etched porous silicon as an anti-reflection coating for high efficiency solar cells, Thin Solid Films (1997) 296–298.
[8] V. Yerokhov, I. Melnyk, A. Tsisaruk, I. Semochko, Porous silicon in solar cell structures, Opto-Electronics Review 8 (2000) 414–417.
[9] M. Lipinski, S. Bastide, P. Panek, C. Levy-Clement, Porous silicon antireflection coating by electrochemical and chemical etching for silicon solar cell manufacturing, Physica Status Solidi (a) 197 (2003) 512–517.
[10] H.-C. Yuan, V.E. Yost, M.R. Page, P. Stradins, D.L. Meier, H. Branz, Efficient black silicon solar cell with a density-graded nanoporous surface: optical properties, performance limitations, and design rules, Applied Physics Letters 95 (2009) 123501-1–123501-3.
[11] P.A. Basore, D.A. Clugston, PC1D, 2002.
[12] A. MacLeod, The Essential MacLeod, Version 8.9.55 (ie), Thin Film Center Inc., 2000, 2001, 2002.
[13] T. Smith, J. Guild, The c.i.e colorimetric standards and their use, Transactions of the Optical Society 33 (1932) 73–134.
[14] H.S. Fairman, M.H. Brill, H. Hemmendinger, How the cie 1931 color-matching functions were derived from the wright-guild data, Color Research and Application 22 (1997) 11–23.
[15] L.A.A. Pettersson, L. Hultman, H. Arwin, Porosity depth profiling of thin porous silicon layers by use of variable-angle spectroscopic ellipsometry: a porosity graded-layer model, Applied Optics 37 (1998) 4130–4136.
[16] D.A.G. Bruggeman, Berechnung verschiedener physikalischer konstanten von heterogenen substanzen. i. dielektrizitätskonstanten und leitfähigkeiten der mischkörper aus isotropen substanzen, Annalen der Physik 416 (1935) 665–679.
[17] C.M. Herzinger, B. Johs, W.A. McGahan, J.A. Woollam, W. Paulson, Ellipsometric determination of optical constants for silicon and thermally grown silicon dioxide via a multi-sample, multi-wavelength, multi-angle investigation, Journal of Applied Physics 83 (1998) 3323–3336.
[18] C. Gueymard, D. Myers, K. Emery, Proposed reference irradiance spectra for solar energy systems testing, Solar Energy 73 (2002) 443–467.
[19] E. Palik, Handbook of Optical Constants of Solids, vol. 1, Elsevier, 1998.
[20] R. Bilyalov, R. Ludemann, W. Wettling, L. Staalmans, J. Poortmans, J. Nijs, L. Schirone, G. Sotgiu, C. Levy-Clemet, Multicrystalline silicon solar cells with porous silicon emitter, Solar Energy Materials and Solar Cells 60 (2000) 391–420.