

Simulation of colouring methods for Silicon PV cells

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Abstract –One of the elements opposed to an increasingly widespread dissemination of photovoltaic systems on residential and public building, is represented by the architectural constraints often imposed on buildings of historical interest or located in neighborhoods where there are strict planning rules. In order to obtain PV systems that meet so severe constraints of integration, it is necessary to rethink the technologies currently used to produce traditional panels; a good compromise between the performance of the panels and the need of a colouring effect as close as possible to the typical red brick of the roofs of buildings subjected to architectural constraints is required.

This paper presents and discusses the state of the art of coloured cells and modules. Based on such a review a novel solution in the field of coloured PV cell techniques is proposed: it simulates the potentialities and limits of using a mixture of precursor gases for the deposition (PECVD) or Sputtering of a reflecting filter on the top of a standard PV Silicon cell.

I. INTRODUCTION

The distributed energy production, possibly in combination with its storage, is a major issue of sustainable development. Photovoltaic systems on residential and public building can contribute to such a process only if economical and aesthetical bounds are overcome. In the Mediterranean sunny regions most of traditional roofs are covered by red tiles, so that the PV modules have also to look tile-red. At present a few commercial products are available with the aim of reaching a satisfactory compromise between aesthetic, efficiency and costs.

In Section II we summarize the state of the art of colored cells or modules and in Section III we focus on the coloured Silicon cells implemented by a single or double layer reflecting filter. In Section III we introduce and discuss our proposed solutions based on double or triple layer reflecting filters.

II. COLOURED PV CELLS: STATE OF THE ART

There are a few commercial products whose technical performances are satisfactory. Their analysis is the starting point for improvements as proposed in scientific literature.

We can classify the different methods of colouring the PV cells or modules according to where the colouring function is allocated:

1) deposition of the colouring layer on the top of the main antireflection layer of the PV cell or instead of it. It represents, at present, a good compromise between aesthetic, efficiency and costs as the thickness of colouring layers do not reduce excessively the efficiency. This technique is the topic of our work and will be discussed in detail in the next section;

2) deposition of a colouring layer onto the inner surface of the front protection layer, usually glass. This technique has been proposed and implemented in [1] and recently announced as a commercial product in [2]. Its main advantage is the use of PV standard cells, the drawback is a colouring layer thickness limited to less than 500 nm in order not to reduce excessively the efficiency;

3) diffusion of the colouring components into the doped cell layer. At present we found no published work. This technique is theoretically interesting if suitable colouring components are investigated and the production volumes are very high, which at present is not the case.

At the Politecnico di Milano we have the facilities (POLIFAB) to afford an experimental research with the first method. This paper presents the preliminary simulations using a mixture of precursor gases SiO₂ and SiNx. These gases are currently used in [1], [3], [4] and [5] in the deposition process but not as a mixture.

II. COLOURED PV CELL ANALYSIS

Fig. 1 shows the front and cross views of a maximum efficiency Single Antireflection Coating (SARC) PV cell (left) and a coloured Double Antireflection Coating PV cell (right).

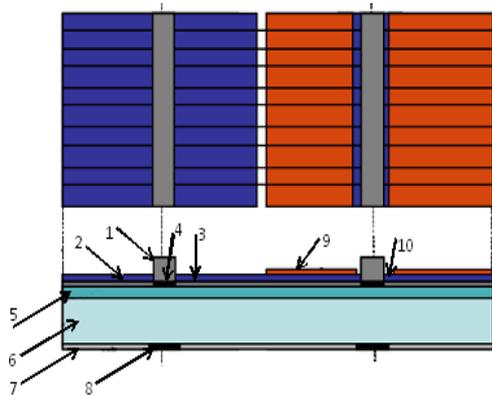


Fig. 1. Optimized cell (SARC) and Coloured cell (DARC). 1 Ribbon (Ag,Zn, ecc.); 2 ARC; 3 FrontBar (Ag/Pd/Ti); 4 Fingers (Ag/Pd/Ti); 5 n-doping; 6 p-doping; 7 Back Surface Field; 8 Back Bus Bar; 9 Colouring layer; 10 Etching for ribbon soldering.

In order to acquire the knowledge of the state of the art we first experimented on a commercial coloured cell by examining its characteristics: reflectivity spectrum, number of layers and their composition. The spectrum of surface reflectivity of a PV module based on these cells (Figure 2) has two maxima, the main at 650 nm and a lower one at 400 nm, and for comparison the reflectivity spectrum of a blue module is also shown. The reason of the higher efficiency of the blue cell is the fact that the solar spectrum has a maximum around 550 nm; the reduction of efficiency as stated by the producer is less than 10%.

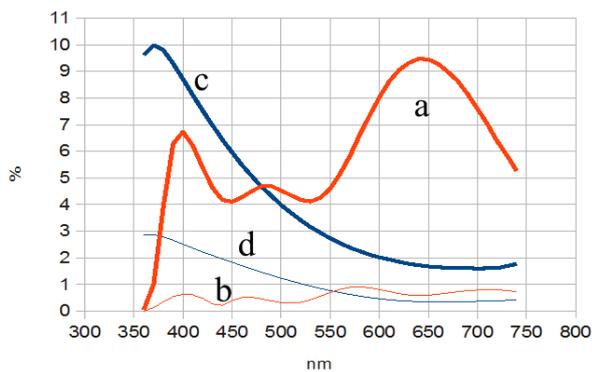


Figure 2. Spectrum of the power reflection coefficients: Coloured cell a) and its standard deviation b). The same for a blue cell [c) and d)]

Figure 3 shows the cross section of another commercial coloured cell, we notice three colouring layers above the anti-reflection Coating (ARC) layer.

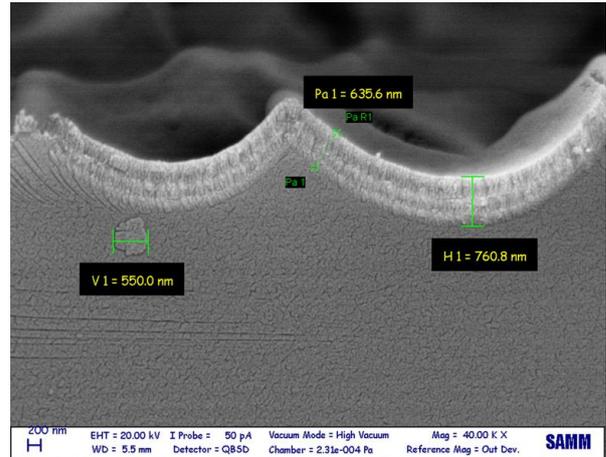


Figure 3 Cross section of a commercial tiled PC cell.

The Energy-dispersive X-ray Spectroscopy (EDS) analysis of the external layers (Figure 4) shows several elements: Si, Mg, F, O and the rare earth yttrium (Y).

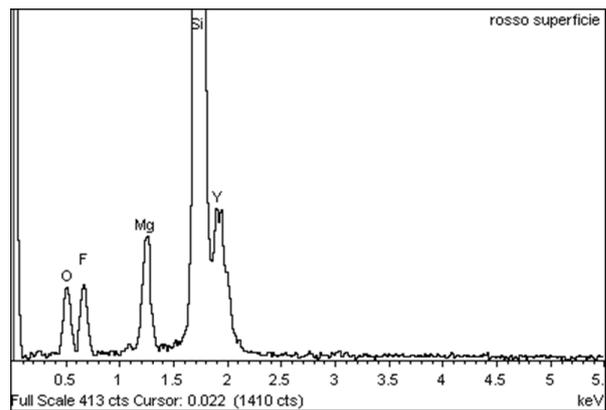


Figure 4 Composition of the colouring layers of the cell in Figure 3.

As a first conclusion we underline the complexity of implementing a successful commercial component; on the other hand our review of the recent literature suggests simpler implementation and composition. In this research we suggest more efficient reflection layers with respect to the ones proposed up to now in [1], [3], [4] and [5].

We first examined the aforementioned scientific researches and simulated their short circuit current density at the STC AMI 1,5 (J_{sc} [mA/cm²]) and their colour, represented by its (xyY) or (RGB) components using the CEI d-65 illuminant. As we are interested in tiled cells only, we defined an allowed triangle region (Table 1) of the (xy) CIE D-65 fan diagram (Figure 5).

The simulations of the SARC and DARC structures are based on the corresponding reflected power coefficient equations. We assume the structure of the PV cell: number of layers, their refraction index (n) and thickness

(d [nm]) and neglect the effects of the angle of incidence of light.

Table 1 The allowed tiled (x,y) region in the CIE diagram (Fig.3)

vertex	x	y
A	0.5	0.5
B	0.65	0.35
C	0.4	0.355

Single Anti Reflection Coating (SARC) structures reported in [1] and [5] have been simulated together with the optimal one [6]. The colour is obtained by a single layer deposited on the reflecting PV cell with refraction index $n_s=3.44$ using a protective front layer with refraction index $n_0=1.5$.

In Table 2 the simulations results for a cell with optimal J_{sc} at $\lambda_0 = 606$ nm and for the coloured cell from [6] are presented.

Table 2 Results of SARC structures

Type	Jsc	n_1	d_1	x	y	Y
Optimum [6]	35.9 8	2.05	74	0.15	0.11	1.33
Coloured [5]	33.4 8	2.3	150	0.51	0.43	14.0 3

Both SARC colour structures [1], [5] give poor results with respect to their corresponding maximum efficiency so that more is expected from multilayers antireflection filters.

Double Anti Reflection Coating (DARC) structures allow higher efficiency and more freedom in the choice of the parameters of the deposited materials. We simulated the works of Y. Chen [3] and M. Li [4] (Table 3 and Table 4).

The colour of the Chen simulation is nearly satisfactory while the one of Li is not.

The simulation program we utilized is different from the more dedicated ones described in the examined papers [3] and [4]; nevertheless we simulated the aforementioned structures with our program and found coherent results.

In both cases the cells have no front protection ($n_0=1$) as it is recommended in practical applications, so we simulated both cases with a protective glass ($n_0=1.5$) and found higher J_{sc} and less satisfying colours; this is due to the lower overall reflection in the modified structures. The lack of a satisfactory front layer protection as glass suggests the necessity of investigating more suitable structures.

The selection of a satisfactory DARC structure requires the simulation of the allowed (n,d) combinations using for instance a trial and error method.

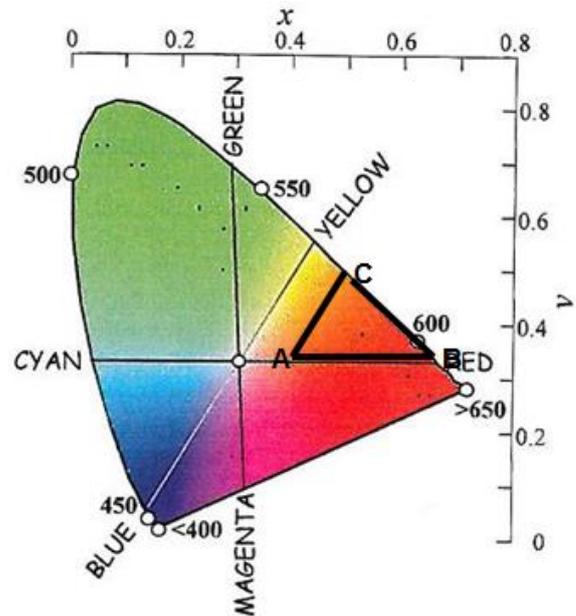


Figure 5 CIE colour diagram with allowed tiled triangle zone ABC

III. THE PROPOSED SOLUTIONS

At Politecnico di Milano we have a facility (POLIFAB) that allows Plasma Enhanced Chemical Vapor Deposition (PECVD) or Sputtering of mixtures (SiON) of SiO_2 and $SiNx$ so that we can design structures with refraction indexes in the range 1.5-2.1 in order to find better solution for the colouring issues.

A. Double Anti Reflection Coating (DARC)

We simulated the performances of DARC structures with the (n,d) layer parameters of

Table 5.

The structure with maximum $J_{sc}= 36.29$ mA/cm² has (n;d)=(1.72; 82 nm). A satisfactory coloured structure (last column in Table 3: PoliMi1) improves the results of the previous simulated researches.

Figure 6 shows the spectrum of the power reflection coefficient: the maximum at 650 nm correspond to that of the commercial cell examined, but the two spectra differ at wave lengths below 450 nm.

The spectrum of the XYZ colour components (Figure 7) confirms the low energy of the blue component (Z) with respect to the remaining ones.

B. Triple Anti Reflection Coating (TARC)

There are at least two motivations for investigating structures with more than one reflecting layer: these structures allow, in theory, and a better colour selectivity and an improvement of the maximum J_{sc} . The colouring effect is obtained by the deposition of a multilayer reflecting filter whose refraction indexes have to be selected in order to obtain the best compromise between efficiency and aesthetic.

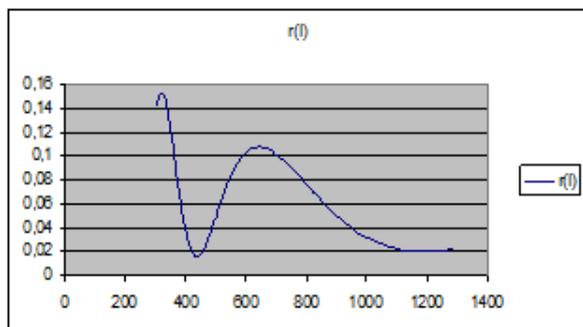


Figure 6 Spectrum of the power reflection coefficient of the PoliMi1 structure

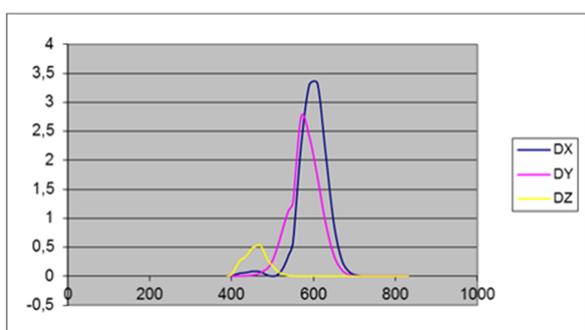


Figure 7 Spectrum of the X, Y, Z colour components of the PoliMi1 structure

The best selective colour reflection is obtained, in theory, with reflecting layers of alternatively high and low refraction indexes [7].

In the case of a multilayer structure we have utilized a general purpose program developed at Politecnico di Milano for geophysical researches in recent years. The main advantage is that it can be applied to quite different types of materials and propagations [8], [9] as optical propagation and reflection.

The program has been upgraded for our purposes so that it can simulate the short circuit current (J_{sc}) using the AM1.5 global spectrum and the colour components (X, Y, Z) using the CIE D-65 illuminant.

We simulated TARC structures implemented by a two layer reflecting filter on the top of a commercial PV cell. In order to find the best compromise we allowed the refraction index to vary from 1.46 to 2.1 (which are the extreme values of a SiON mixture) with 0.02 steps and the thickness to vary from 30 nm to 150 nm with a 2nm step (which are technologically reasonable practical limits). Each (n,d) combination is associated with a model number.

The program simulates all the five million modelled structures; only the ones with $J_{sc} > 35 \text{ mA/cm}^2$ and normalized colour components (x,y) inside the ABC triangle of Fig. 3 are memorized for further analysis. The characteristics of the 7000 satisfactory models are

summarized in Figure 8

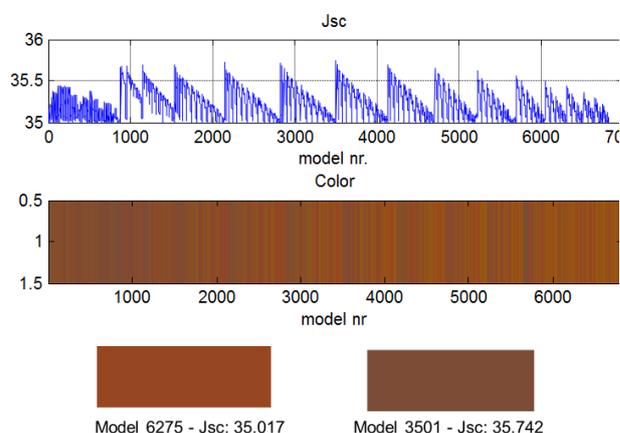


Figure 8 Characteristics of TARC models and two models colour simulation

This Figure shows at its top the J_{sc} values versus their model number, the middle of the Figure shows the resulting colour of each model and the bottom the colours of two specific models (6275 and 3501). Table 6 gives the parameters and performances of the model optimized for J_{sc} and of the two selected models 6275 and 3501. The trade-off between J_{sc} performance and colour is estimated better for model 6275, moreover its sequence of the refraction indexes from the front layer (1.5; 2.0; 1.54; 2.05; 3.44) is typical of a selective filter [7].

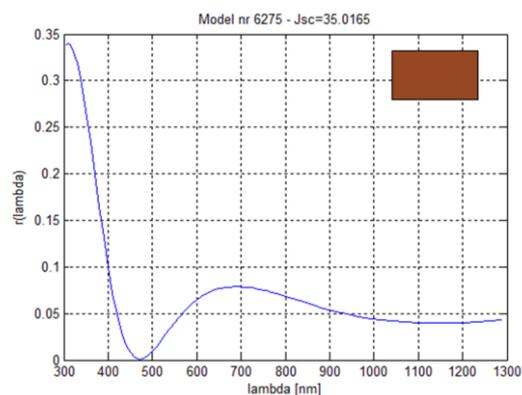


Figure 9 Spectrum of the power reflection coefficient of the TARC model n.2275 and its RGB colour and parameters

Figure 9 represents the spectrum of the power reflection coefficients and put in evidence a higher reflectivity at long wavelengths (more red color) and a higher absorption at short wavelengths (useful at noon in clear days) both being benefits with respect to the DARC structure (see Figure 6).

IV. CONCLUSION

The paper has reviewed the state of the art of commercial and research coloured PV cell and found significative differences. Specifically the examined research coloured PV cells operate in an environment not suitable for actual applications. We therefore investigated structures whose cells are front protected by glass and use as precursors gases mixtures of the ones usually used alternatively.

We simulated coloured PV cells using either single or double reflecting layers on the top of the standard blue cell and obtained quite satisfactory results with respect to efficiency and to tiled colour.

The current activity has given the specifications for the deposition process of the proposed colored cells as the preliminary step for an implementation of prototyping coloured PV cells at the POLIFAB of Politecnico di Milano. We hope to start with the simpler DARC structure as a validation of the basic ideas and, if the case, follow with a more efficient TARC structure.

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REFERENCES

[1] P. Bouchut et al.: "Colored Photovoltaic Modules for Better Architectural Integration", 27thEUPVSEC 2012
 [2] www.wissinsol.com

[3] Y. Chen et al.: "Color Modulation of c-Si Solar Cells without significant Current-loss by Means of a Double-layer Anti-reflective Coating", 27thEUPVSEC 2012
 [4] Minghua Li, L. Zeng, Y. Chen, L. Zhuang, X. Wang, H. Shen "Realization of Colored Multicrystalline Silicon Solar Cell with SiO₂/SiN_x:H Double Layer Antireflection Coatings" International Journal of Photoenergy Vol. 2013, 8 pages, Article ID 352473 Hindawi Publishing Corporation
 [5] I. Tobias, A. El Moussaoui, A. Luque: " Colored Solar Cells with Minimal Current Mismatch" IEEE Transactions on Electron Devices Vol 46 n.9 1999 (pp.1858-1865)
 [6] M.A. Green: "Solar Cells: Operating Principles, Technology and System Applications" the University of New South Wales 1998
 [7] O.S. Heavens: "Optical properties of Thin Solid Films" Dover Publication Inc. 1991
 [8] Kind, R., Computation of reflection coefficients for layered media, Journal of Geophysics, 42, 191-200, 1976
 [9] Kennett, B., Reflections, rays and reverberations, Bulletin of the Seismological Society of America, 64, 1685-1696, 1974.

Table 3 Coloured DARC characteristics

Author	Chen	Li	PoliMil
L.0: material;n0	air;1	air;1	glass;1.5
L.1:material, n1; d1	SiO ₂ , 1.54; 128	SiO ₂ , 1.46; 136	SiON, 1.9; 90
L.2: n2; d2	2.05; 76	2.1; 80	2.05; 80
Jsc: sim; actual	34.39; 36.40	35.08; 34.91	34.48; n.a.
X; Y; Z	10.97; 6.89; 9.52	6.48; 2.97; 17.89	12.99; 11.59; 3.97
x; y	0.40; 0.25	0.24; 0.11	0.46; 0.41
in ABC region	Near	No	Yes
sim. colour	red/magenta	blue/magenta	yellow/red
R; G; B	15.3; 5.02; 9.57	4.27; 2.49; 18.05	18.50; 10.19; 3.91
actual colour	red	Purple	n.a.

Table 4 Meaning of the rows in Table 3

Row	Meaning
L.0: material;n0	Upper layer: air or glass; corresponding refraction index
L.1:material, n1;d1	Colouring Layer: material: SiO ₂ or SiON (mixture of SiO ₂ and SiN _x), refraction index and thickness
L.2: n2; d2	Antireflection Layer: SiN _x : refraction index and thickness
Jsc: sim;actual	Jsc: simulated; actual from literature
X;Y;Z	X, Y, Z colour components (from simulated reflectivity spectrum)
x;y in ABC region	Simulated normalized x,y colour components for CIE fan diagram Accordante with proposed tiled color
sim. colour	Simulated colour from CIE diagram
R;G;B	RGB colour components for screen visualisation (e.g. Power Point)
actual colour	Actual colour from literature

Table 5 (n;d) values used for the proposed structures at Politecnico di Milano

	Glass	Colour.Layers	ARC	m-Si
n	1.5	1.4-2.3	2.05	3.44
d (nm)	4.10 ⁶	30-150	80	2.10 ³

Table 6- Characteristics of two TARC simulated models

Model	n ₁	d ₁	n ₂	d ₂	Jsc	X	Y	Z	x	y	R	G	B
Max J _{sc}	1.64	30	1.48	36	36.00	3.27	3.39	6.80	0.243	0.252	1.50	3.75	6.84
6275	2	36	1.54	46	35.017	5.31	3.99	1.56	0.489	0.367	8.30	3.09	1.9
3501	1.9	30	1.46	42	35.740	3.39	3.09	1.68	0.415	0.379	4.50	2.80	2.03