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Theoretical comparison of two-dimensional transient analysis between back and front laser treatment of thin multilayer films

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Abstract

In this paper a comparison between two manufacturing processes is carried out by means of pulsed laser heat sources of thin film on substrate. The heat source can either impinge directly on the film surface (front treatment), or on the substrate (back treatment). A transient combined nonlinear optical-thermal model for pulsed laser sources on a thin film-glass substrate is proposed. The radiative field is considered to be locally one-dimensional and the transient conductive field two-dimensional. The investigation is carried out for a Nd-YAG laser with wavelength of 1064 nm impinging on an amorphous silicon (a-Si)/transparent conductive oxide SnO_2 (TCO) thin film deposited on a glass substrate. This is a step of the manufacturing process of amorphous silicon (a-Si) photovoltaic cells. Results in terms of radiative coefficients, temperature and absorption function distributions are presented in order to compare the two processes. The analysis shows that the highest values of absorptivity and temperature are obtained in the back treatment. Therefore this manufacturing process is more efficient for the production of photovoltaic cells.

Keywords: Multilayer thin films; Pulsed lasers; Combined heat transfer; Conductive–radiative heat transfer; Numerical analysis

1. Introduction

In recent years engineering and technological applications of thin films have developed greatly. This is particularly true for the manufacturing of silicon components and sensors and in the evaluation of the optical properties of single and multilayer systems. It has also been necessary to further the thermal analysis in the manufacturing processes of thin films, those relevant to electronic components and photovoltaic cells, for example. Thermal treatment of thin film manufacturing processes with pulsed laser is a common procedure [1]. In these manufacturing processes the heat source impinges on a very small area and a very high heat flux is obtained, so that localized overheating occurs. Since the optical properties of materials in thin films depend generally on the wavelength of the heating laser and on temperature, a thermally optical nonlinearity is induced. The analysis of thermal conductive and optical distributions is therefore important in order to broaden their field of application and to improve their control. Experimental and computational investigations of pulsed laser interactions with single or multilayer thin films on a glass substrate were performed [2,3].

Laser manufacturing of thin films on a substrate can be done in two different ways, as showed in Fig. 1. In the first, called "front treatment" (FT) Fig. 1(a), the laser beam impinges directly on the external film surface; in the second, called "back treatment" (BT) Fig. 1(b), the laser beam hits the external substrate surface, directly. The two techniques present distinct patterns as far as the radiative characters of the structure is concerned.

Recently, Kumar et al. [4] measured the transmittance and reflectance of superconductive $YBa_2Cu_3O_{7-6}$ (YBCO) thin films on Si substrates in the far-infrared wavelength (100–1000 μm) at temperatures between 10 and 300 K. They showed that the backside reflectance (radiation incident on the substrate side) increased significantly from the normal

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Nomenclature

A	absorptivity	
c	specific heat	$J\cdot kg^{-1}\cdot K^{-1}$
I_0	maximum laser irradiance	$W\cdot m^{-2}$
k	thermal conductivity	$W\cdot m^{-1}\cdot K^{-1}$
k_{ext}	extinction coefficient	
N	number of layers	
$n, \bar{n}$	real part and complex refractive index	
R	reflectance	
r, z	radial and depth coordinate	m
S	Poynting vector	$W\cdot m^{-2}$
s	material thickness	m
T	temperature	K
t	time	s
$\dot{u}'''$	absorption function	$W\cdot m^{-3}$

Greek symbols

λ	wavelength	m
ρ	density	$kg\cdot m^{-3}$
τ	transmittance	

Subscripts

g	Gaussian
i	material
in	initial
l	length
p	peak
s	substrate

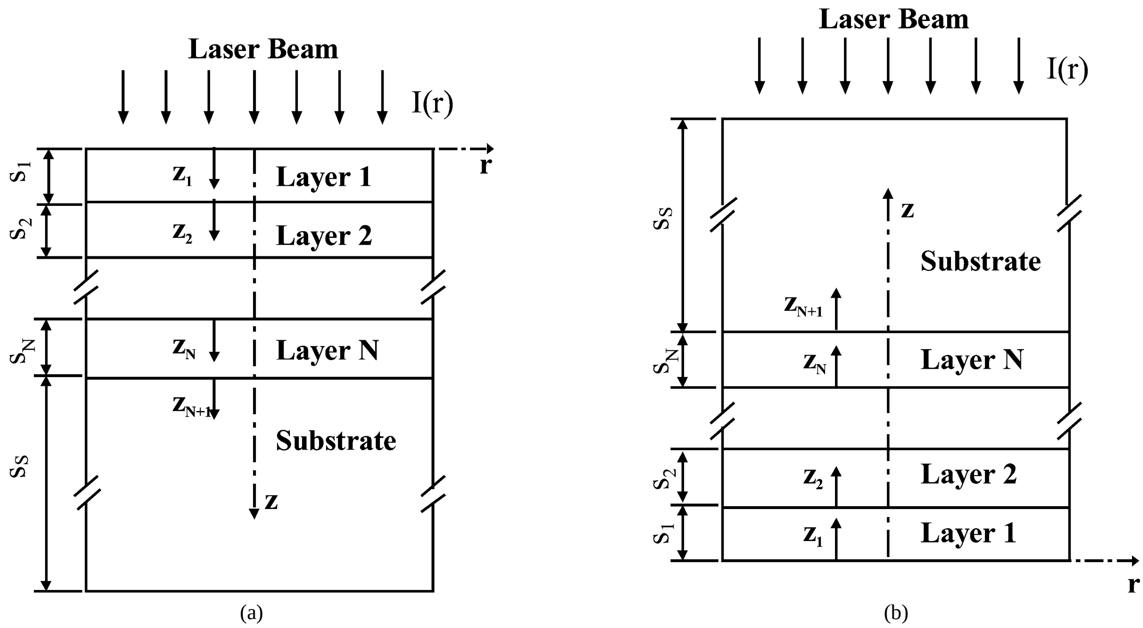

Fig. 1. Sketch of the processes. (a) Front treatment; (b) back treatment.

state to the superconductive state at certain wavelengths. Bianco et al. [5,6] compared the BT and FT processes in terms of the optical characteristics and temperature distributions of a single TCO layer, a-Si/TCO and Al/a-Si/TCO multilayers. The results were obtained by means of an optical and thermal one-dimensional model and were related to a Nd-YAG laser source with a wavelength of 1064 nm. The analysis clearly showed that the BT is more efficient in the photovoltaic cells manufacturing process. Avagliano et al. [7] carried out the numerical and experimental analysis of laser BT of a-Si photovoltaic cells made out of a multilayer thin film on a glass substrate. The experimental and numerical results were in good agreement.

The combined optical-conductive analysis of the temperature fields and optical characteristics in thin films was studied by several investigators as reviewed by Bianco and Manca [3]. In the following only the multidimensional studies are briefly reviewed. For a multilayer-thin film structure irradiated by a circular Gaussian laser beam, a numerical model was proposed by Nakano et al. [8]. Kiyama et al. [9] extended the numerical model presented in [8] to the multilayer thin films with temperature dependent thermal properties and constant optical properties, moreover in this paper they solved the optical field by means of the matrix method for the FT process. They wrote the heat conduction equation for a transient three-dimensional thermal field, also considering the possible melting. They presented temperature distributions along only the depth coordinate and no information was given about the temperature dependence on the other spatial coordinates. Madison and McDaniel [10] obtained a solution for a scanned and pulsed Gaussian laser beam for an N-layer film structure. A local Green's function theory for temperature evaluation in an isotropic multilayer materials was presented by McGahan and Cole [11]. Machlab et al. [12] developed an experimental technique for thermal diffusivity measurements of thin films. Cole and McGahan [13] extended the theory presented in [11] to include anisotropic thermal properties and contact resistance between the layers.

The lack of a comparison between BT and FT for multidimensional problems (given by Bianco et al. [5,6] as regards the one-dimensional problem) is the reason for the present study. This paper has three aims:

(a) to enlarge the analysis proposed by Bianco and Manca [3] to multilayer thin films;
(b) to compare the results of BT and FT obtained by a two-dimensional conductive model for different multilayer thin films;
(c) to identify the best process between FT and BT for the manufacturing of a-Si photovoltaic modules.

As far as point (a) is concerned, the proposed analysis allow to enlarge the study proposed in [3] on a single a-Si thin film deposed on a glass substrate to a multilayer thin film made of a TCO and an a-Si layer also in this case deposed on a glass substrate. This kind of structure is encountered in one of the phases of the a-Si photovoltaic cells manufacturing process. The aim (b) is related to the two-dimensional comparison between the FT and BT processes. The extension to a 2-D model allows the evaluation of the thermal gradients along the direction normal to the beam propagation. In this way it is possible to evaluate the extension of the heat affected zone in the two processes. This evaluation is clearly not possible with a one dimensional model. Finally, point (c) is related to scribing of the a-Si layer in the photovoltaic cells manufacturing process. In this case the best process, between FT and BT, is the one that allow the scribing with the less amount of laser power and with the less extension of the heat affected zone, as reported in [7]. The proposed model does not take into account the melting of the materials. The evaluation of the best process has been done in terms of maximum temperature values reached in the two processes.

A combined optical-thermal model for a pulsed laser source on a thin film-glass substrate is proposed. The stationary laser beam is orthogonal to the target, the radiative field in thin film structure is considered locally one-dimensional (1-D). This means that the optical field depends on the depth coordinate, but also on the radial coordinate, due to the variation of the optical properties along this direction. The optical field can be assumed locally one-dimensional due to the laser source that impinges orthogonally to the multilayer. Possible distortions of the optical path along the radial direction are neglected. In fact the real part of the refractive index has been assumed constant and self-focusing phenomena are not present [14]. The transient conductive field inside the solid is two-dimensional. The solid dimension along the normal direction to the laser beam is infinite. Both optical and thermal properties are temperature dependent. The one-dimensional optical model is solved by means of the classical matrix method in multilayer theory, and the two-dimensional heat conduction equation, in cylindrical coordinate, is numerically solved by means of a finite volume method. This model is more complete of a linear one, in fact in this case it is possible to take into account the combined effects of the optical and thermal fields.

The analysis is obtained for a multilayer thin films on a glass substrate. A step of the manufacturing process of amorphous silicon (a-Si) photovoltaic cells, made of a multilayer structure TCO/a-Si, is analyzed in details. In this paper the TCO considered is SnO_2. The solid structure is irradiated by a pulsed laser with a wavelength of 1064 nm. A time dependence triangular shape of the laser beam is taken into account; whereas the spatial dependence is Gaussian. The results and the comparison between BT and FT, in terms of radiative coefficients, temperature and absorption function distributions are presented.

2. Model description and analysis

The investigated workpiece is made up of a multilayer thin film deposited over a glass substrate. The substrate is considered as being thermally seminfinite and it is assumed not to interact with the incident light. The investigated solid is irradiated by a pulsed Nd-YAG laser source with a single triangular pulse, employed in some applications such as the amorphous silicon photovoltaic cells manufacturing [7]. For the nanosecond time scales considered in this work, non-equilibrium and non-Fourier thermal wave effects are negligible as suggested by Chen and Tien [2]. Two photon absorption, interlayer gradients and photoinduced piezoelectric-electrostatic effects are neglected. The thermal and the optical properties are considered temperature dependent and the materials are considered isotropic. For the investigated time intervals, the radiative and convective heat losses from the thin film surface toward the ambient can be neglected. Self-focusing or de-focusing phenomena are not present since the real part of the refractive index is constant [14].

With reference to Fig. 1, by employing a local reference system for each layer of thickness s_i, the conductive problem, in cylindrical coordinate (r, z), is:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rk_i(T)\frac{\partial T_i}{\partial r}\right)+\frac{\partial}{\partial z_i}\left(k_i(T)\frac{\partial T_i}{\partial z_i}\right)+\dot{u}'''(T,r,z,t) = \rho_i c_i\frac{\partial T_i}{\partial t} \qquad (1)$$

where $i = 1, 2, \ldots, N+1$ and for $0 \leqslant r < \infty$, $0 \leqslant z_i \leqslant s_i$, $t > 0$, with $s_{N+1} \to \infty$, N being the number of layers.

The initial and boundary conditions are:

$$T_i(r, z_i, 0) = T_{\text{in}} \qquad i = 1, 2, \ldots, N+1,\ 0 \leqslant r < \infty,\ 0 \leqslant z_i \leqslant s_i \qquad (2a)$$

$$\frac{\partial T_1(r,0,t)}{\partial z_1} = 0 \qquad t \geqslant 0,\ 0 \leqslant r \leqslant \infty \qquad (2b)$$

$$k_{i-1}\frac{\partial T_{i-1}(r,s_{i-1},t)}{\partial z_{i-1}}=k_i\frac{\partial T_i(r,0,t)}{\partial z_i}\quad i=1,2,\ldots,N,\ t\geqslant 0,\ 0\leqslant r\leqslant\infty \tag{2c}$$

$$T_{i-1}(r,z_{i-1},t)=T_i(r,0,t)\quad i=1,2,\ldots,N,\ t\geqslant 0,\ 0\leqslant r\leqslant\infty \tag{2d}$$

$$T_{N+1}(r,z_{N+1}\to\infty,t)=T_{\text{in}}\quad t\geqslant 0,\ 0\leqslant r\leqslant\infty \tag{2e}$$

$$T_i(r\to\infty,z_i,t)=T_{\text{in}}\quad i=1,2,\ldots,N+1,\ t\geqslant 0,\ 0\leqslant z_i\leqslant s_i \tag{2f}$$

The term $\dot{u}'''(T,r,z,t)$ is related to the Poynting vector S by means of:

$$\dot{u}'''(T,r,z,t)=\pm f(t)\frac{\partial S(r,z,t)}{\partial z} \tag{3}$$

where the plus sign is for the FT case and the minus sign is for the BT one. $f(t)$ is a function that characterizes the temporal shape of the pulse. In this work a triangular time profile is considered, as proposed by Park et al. [15]: $f(t)=t/t_p$ for $0\leqslant t\leqslant t_p$; $f(t)=(t_l-t)/(t_l-t_p)$ for $t_p\leqslant t\leqslant t_l$; $f(t)=0$ for $t>t_l$. The influence of the time profile have been analyzed in [16] for the 1-D model. The incident intensity distribution can be written as:

$$I(r)=I_0\exp\left(-\frac{r^2}{r_0^2}\right) \tag{4}$$

where r_0 is the spot radius.

The S evaluation is made by the classical matrix method following the analysis proposed in [3].

The conductive temperature field is numerically obtained by means of a fully implicit finite volume method. The numerical solution of the model has been obtained iteratively at each time step with the temperature dependent source distribution by means of the ADI method [3]. The numerical procedure has been validated in [3] by comparing its solution with that of the one-dimensional model presented in [17]. The problem has been made one-dimensional by considering the heat source uniform along r and negligible differences between the two models have been found both in terms of temperature fields and heat generation fields. A grid dependence test has been carried out to determine the appropriate grid size. Details on the validation of the numerical procedure can be found in [3]. So, the medium refined grid has been chosen for the calculations because it has adequate accuracy. In this study a double layer of a-Si and TCO on a glass substrate has been considered, where layer 1 is a-Si and layer 2 is TCO. The TCO layer is 600 nm thick and it is subdivided into 60 nodes along the z direction. Two different a-Si thicknesses of 500 and 1000 nm have been considered and in all cases a spatial step along the z direction of 10 nm has been chosen. The entire period of time considered in this work is 60 ns and a depth of 10 μm is sufficient to consider the glass as thermally semi-infinite. In all cases the number of nodes in the substrate along the z coordinate is 300. A Gaussian laser source with a beam radius of 20 μm has been considered; the number of nodes in the r direction is $N_r=100$ in all cases and a radius of 100 μm is sufficient to consider the computational domain infinite along the r direction. Both in the thin films and in the glass substrate the spatial step along the z-direction is uniform. The distance between two nodes along the r-direction is nonuniform and it is equal to $I\Delta r_0$, with $\Delta r_0=15.6$ nm, and I equal to $1,2,\ldots,N_r$. A time step of 5.0×10^{-2} ns has been chosen, since a smaller time step had no significant influence on the results. A relative error in the iteration procedure of 10^{-6} has been chosen.

3. Results and discussion

The numerical solution is analyzed to evaluate the difference between back and front treatment in terms of optical characteristics, temperature distributions and absorption function. These functions are calculated for a double layer of a-Si and TCO on a glass substrate. The optical and thermal properties of materials are reported in Table 1. As has already observed in the previous section, a triangular pulse has been considered. The ON phase and the peak time of the triangular pulse are 30 ns and 6 ns, respectively; the spot radius is equal to 20 μm. The laser irradiation wavelength is 1064 nm. The heat flux distribution is Gaussian and I_0 value is 1.0×10^{11} W·m^{-2}. The layer thicknesses are 600 nm for the TCO and 500 and 1000 nm for the a-Si.

Radiative coefficients as function of the time at some r values for front and back treatments are reported in Fig. 2. In this figure the results related to the two different values of the a-Si thickness are shown. A small variation of these quantities is observed with respect to the linear value as time increases. This is due to the temperature dependence

Table 1
Optical and thermophysical properties

	k [W·m^{-1}·K^{-1}]	c [J·kg^{-1}·K^{-1}]	ρ [kg·m^{-3}]	$\bar{n}=n-ik_{\text{est}}$ ($\lambda=1064$ nm)
Glass	1.4 [20]	1200 [20]	2200 [20]	$1.46-i\ 0.0$ [20]
TCO (layer 2)	$39.6-2.09\times10^{-2}(T-273.15)$ $+4.62\times10^{-6}(T-273.15)^2$ [9]	$371.0+0.217(T-273.15)$ [9]	6640 [9]	$1.95-i\ 0.002$ [9]
a-Si (layer 1)	$1.3\times10^{-9}(T-900)^3$ $+1.3\times10^{-7}(T-900)^2$ $+10^{-4}(T-900)+1.0$ [21]	$952.0+(171.0T)/685$ [9]	2330 [21]	$3.8-i[0.0443+6.297\times10^{-5}(T-273.15)]$ [19]

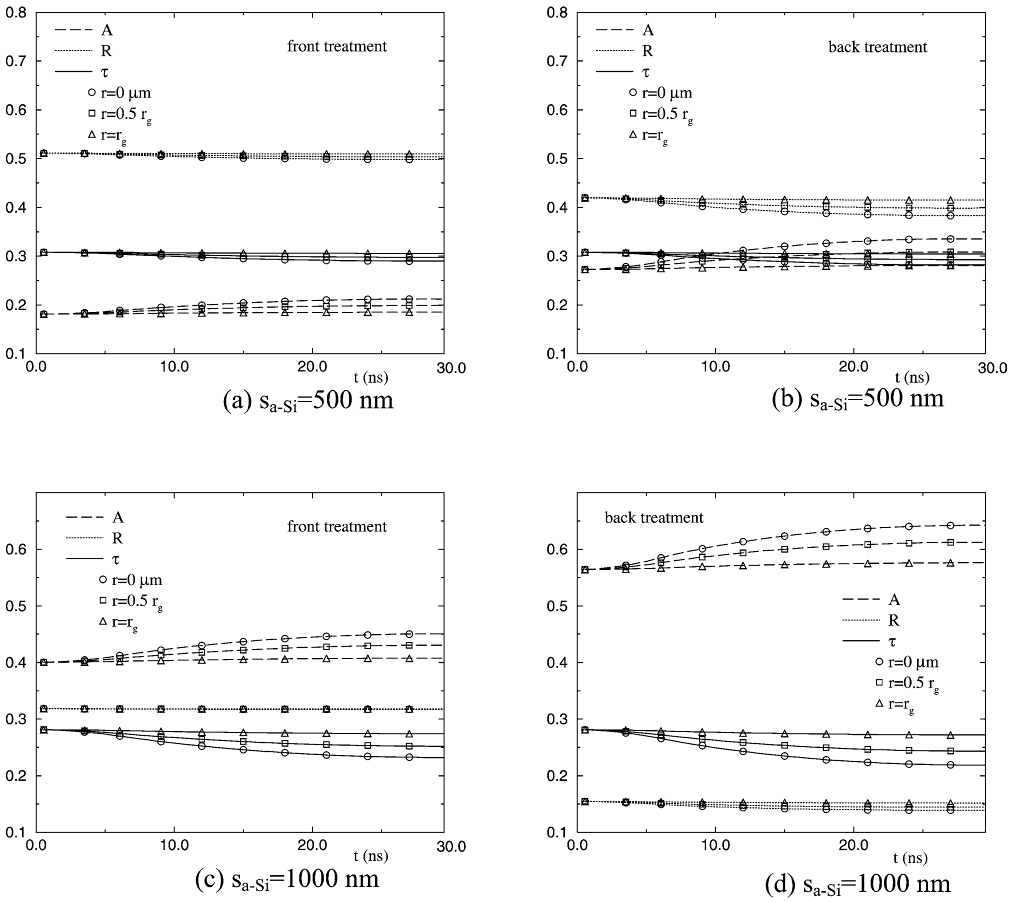

Fig. 2. Radiative coefficients as function of t for several r values for front and back treatments. $I_0 = 1.0 \times 10^{11}$ W·m^{-2}, $s_{\text{a-Si}} = 500$ and 1000 nm.

of the optical and thermal properties. In all cases the absorptivity increases with time, whereas the trasmittance and the reflectance decrease. For an a-Si thickness equal to 1000 nm (Fig. 2(c) and (d)) the reflectance is almost constant for front and back treatment. For the BT case (Fig. 2(d)) the A coefficient shows higher values than the corresponding ones for the FT case (Fig. 2(c)) for all r values. This figure shows that the differences of R, A and τ values along r are larger for the BT case than for the FT one. This is true also for the linear case, due to the different optical pattern of the incident light for the two treatments, but in this case a one-dimensional model is sufficient to describe the process. In the nonlinear case this difference is greater than in the linear one due to the temperature dependent optical properties. R values are lower for the BT case than the corresponding ones for the FT case, whereas τ values are almost the same for the two cases. Small differences between τ values for the FT and BT cases are due to the temperature dependence of the optical properties. In fact, for a multilayer composed with linear materials the transmittance does not change if the light source impinges on the back or front surface as required by the energy transfer reciprocity [5,18]. The radiative coefficients present an oscillating behavior with respect to the a-Si thickness as reported in [5], this explains the great variation of absorptivity and reflectance for the two considered a-Si thicknesses.

The reflectance R, the transmittance τ and the absorptivity A of the a-Si/TCO/glass structure as function of the radial coordinate for $t = 6$ ns (peak time) and $t = 15$ ns and for two a-Si thicknesses are reported in Fig. 3 for $I_0 = 1.0 \times 10^{11}$ W·m^{-2}. In the optical linear case A, R and τ are uniform along the radial coordinate, whereas in the nonlinear case the two-dimensional thermal field induces a two-dimensional optical field due to the temperature dependent optical properties. The radiative field is assumed locally one-dimensional, in this way the mutual effect between optical and thermal fields is considered. The diagrams show that the asymptotic values of radiative coefficients are those of the linear case. At the center of spot ($r = 0$) the absorptivity values are higher than those in the linear case due to the highest value of the irradiance and the corresponding highest temperature value for the considered thickness. This difference is higher at 15 ns than at 6 ns because of the higher temperature values. The difference between the reflectance values at $r = 0$ and $r \to \infty$ ($r = 50$ μm) for the FT case (Fig. 3(a) and (c)), and the BT case (Fig. 3(b) and (d)) decreases with the thickness. These effects are more marked for $I_0 = 2.0 \times 10^{11}$ W·m^{-2}, Fig. 4. Due to the dependence of the optical prop-

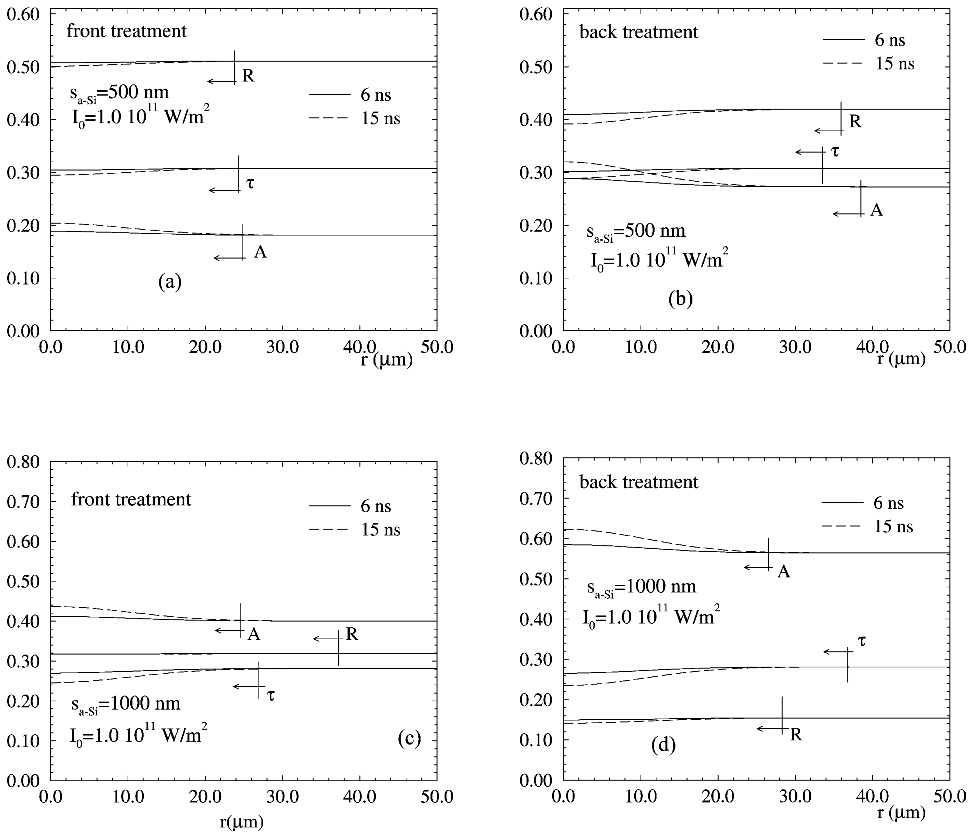

Fig. 3. Radiative coefficients as function of r for several t values for front and back treatments. $I_0 = 1.0 \times 10^{11}$ W·m^{-2}, $s_{\text{a-Si}} = 500$ and 1000 nm.

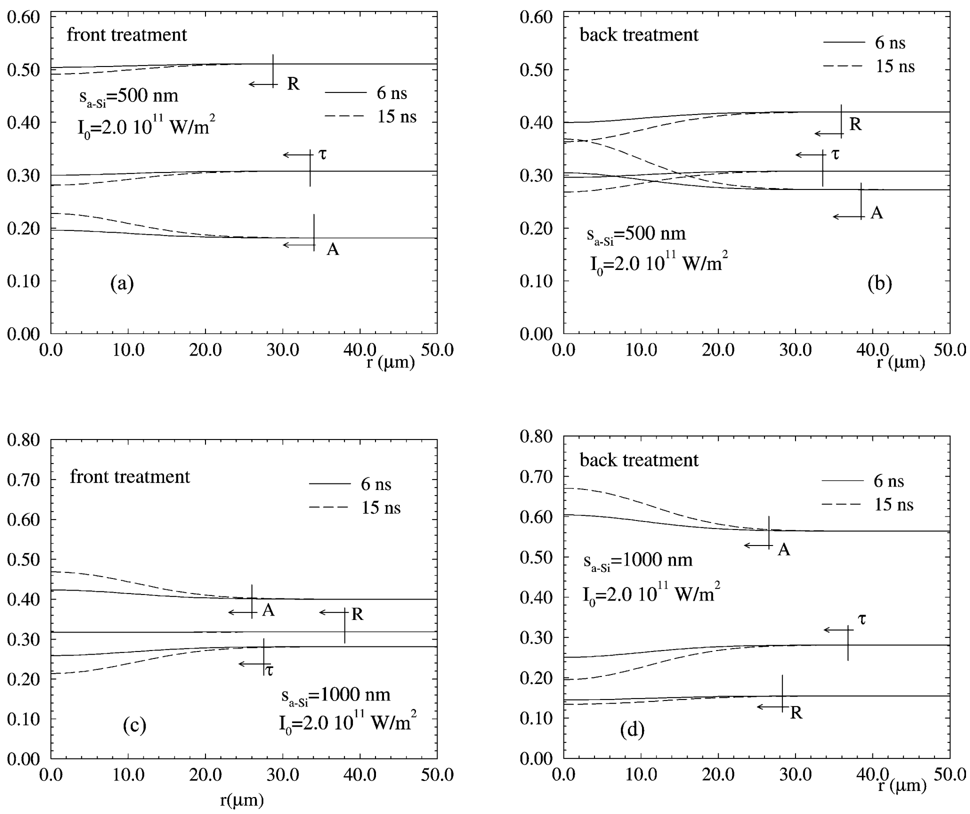

Fig. 4. Radiative coefficients as function of r for several t values for front and back treatments. $I_0 = 2.0 \times 10^{11}$ W·m^{-2}, $s_{\text{a-Si}} = 500$ and 1000 nm.

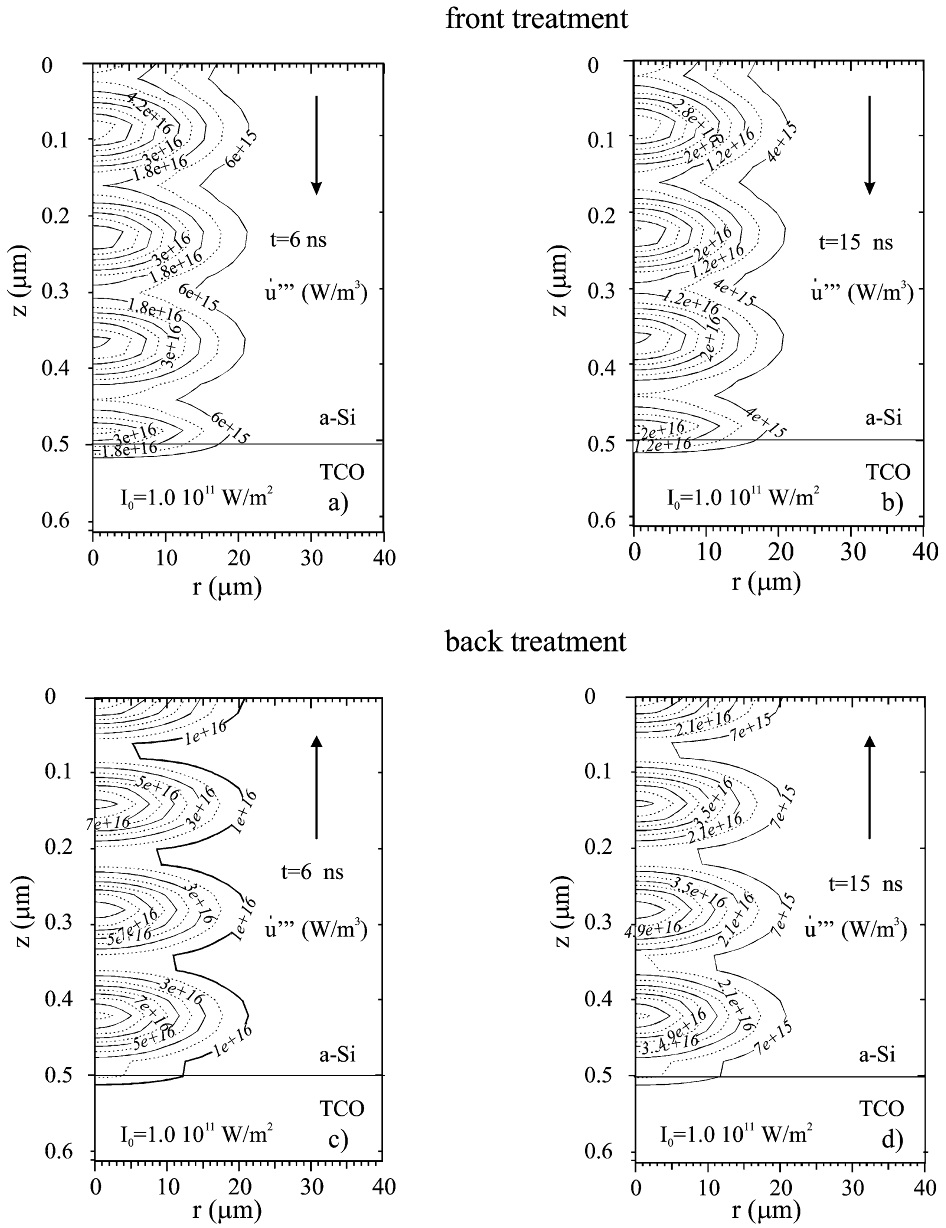

Fig. 5. Absorption function distributions for several t values for front and back treatments. $I_0 = 1.0 \times 10^{11}$ W·m^{-2} and $s_{\text{a-Si}} = 500$ nm.

erties on the r coordinate, it needs a comparison between the values related to a 2-D model.

In Fig. 5 the absorption function field for FT and BT and for $t = 6$ ns and 15 ns are reported. In these figures the differences between front and back treatment are more evident. The absorption function fields are similar for FT and BT cases even if in the latter case the $\dot{u}'''$ values are higher because of the higher absorptivity values, as seen in Figs. 2 and 3. The absorption function presents relative maxima for z values equal to almost 1/4 of the inside a-Si wavelength according to Chen and Tien [2]. The absorption within the TCO is one order of magnitude lower than the a-Si one and so it is not shown in the figures. The maximum of $\dot{u}'''$ is attained inside the a-Si layer, and it can be observed that for the FT case the $\dot{u}'''$ values on the a-Si surface presents higher differences with respect to the maximum than the BT case values.

In Fig. 6 thermal fields for FT and BT cases, for an a-Si thickness of 500 nm, are reported. Figs. 6(a)–(c) show that for FT case, maximum temperature values are attained inside the a-Si layer at $t = 6$ ns, according to the absorption function reported in Fig. 5. As t increases these values move to the surface of the layer. The thermal gradients in the TCO layer decrease as time increases. For the BT case (Fig. 6(d)–(f)) maximum temperature values are higher than the corresponding ones for the FT case due to the higher absorptivity values. The maximum value is attained inside the a-Si layer even for $t = 30$ ns at the center of the spot ($r = 0.0$ μm). For r equal to about 5 μm, the maximum temperature is attained at the a-Si surface. In the FT case,

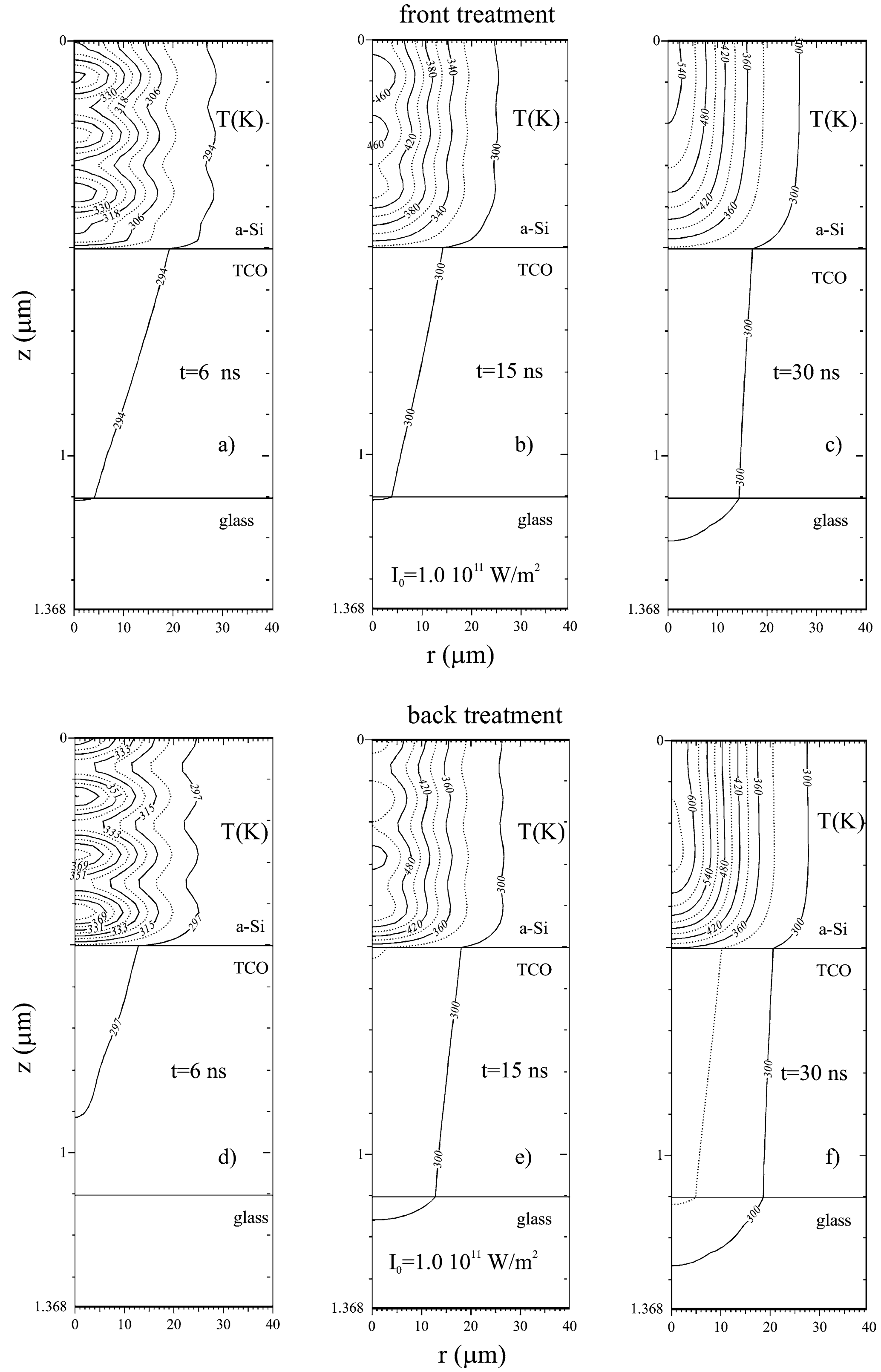

Fig. 6. Temperature distributions for several t values for front and back treatments. $I_0 = 1.0 \times 10^{11}\ \mathrm{W{\cdot}m^{-2}}$ and $s_{a\text{-}Si} = 500$ nm.

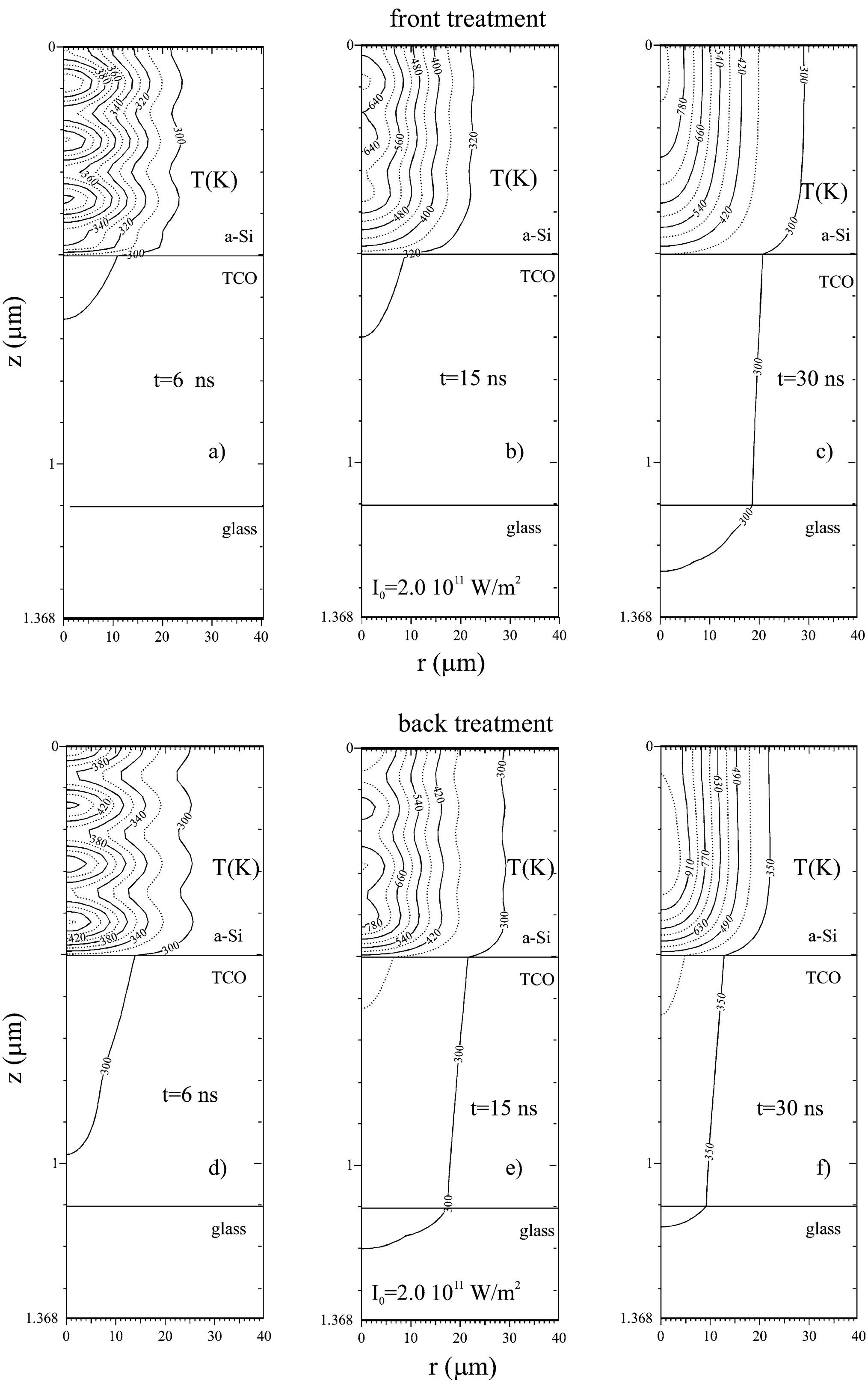

Fig. 7. Temperature distributions for several t values for front and back treatments. $I_0 = 2.0 \times 10^{11}\ \mathrm{W{\cdot}m^{-2}}$ and $s_{\text{a-Si}} = 500$ nm.

Table 2
Percentage a-Si surface temperature differences between $r = 0$ and $r = r_g$ at the end of the laser pulse

	$[T(0,0,t_p) - T(r_g,0,t_p)]/T(0,0,t_p)$	
I_0 [W·m^{-2}]	FT	BT
1.0×10^{11}	40%	46%
2.0×10^{11}	57%	59%

for $t = 30$ ns, maximum temperature values are attained at the a-Si surface for all r values. The analysis of the thermal field shows that in the BT case the possible melting can start inside the a-Si layer in a zone near the spot center. The two-dimensional analysis allow the evaluation of the extension of the heat affected zone. This evaluation gives useful information on the possible cut thickness and on its quality with respect to the regularity of the boundaries. In fact the melting and the following vaporization of the material inside the layer could give a cut with irregular boundaries. In the BT case temperature values also in the TCO layer and in the glass substrate are higher than in the FT case. It was observed that for I_0 equal to 2.0×10^{11} W·m^{-2}, Fig. 7, the difference between BT and FT are greater than in the previous case. This is due to the larger absorption related to the higher temperature values reached in this case. This remarks the mutual effect between the thermal and the optical fields. The extent of the heat affected zone is of the same order of magnitude of the spot radius. This is important from a technological point of view, in fact if the zone to be treated is known, the beam radius can be chosen. Another advantage is that the characteristics of the material not directly irradiated by the laser are not influenced by the thermal fields. The heat affected zone is larger in the BT case than in the FT one both at the a-Si surface and inside the a-Si layer. At the same z values, temperatures are higher in the BT case than in the FT one. Due to the higher thermal conductivity of the TCO than that of the a-Si, large thermal gradients along the z coordinate are present inside the a-Si layer near the a-Si/TCO interface. It is worth noting that in this analysis the thermal gradients along the z coordinate are lower than those in the one-dimensional conductive model.

In Table 2 the percentage difference between the a-Si surface temperature values at the spot center and at $r = r_g$, at the end of the laser pulse, are reported for the FT and BT cases and for the two considered I_0 values. This values allow an estimation of the cut width, this is clearly not possible with a one-dimensional model.

4. Conclusions

A comparison between two laser treatments on multilayer thin films deposited on a glass substrate was accomplished. The laser source can either impinge on the film surface (front treatment), or on the substrate (back treatment). A step of the manufacturing process of amorphous silicon photovoltaic cells was investigated.

The combined optical-conductive problem in a-Si/TCO thin film structure on a glass substrate was numerically analyzed. The radiative field was considered locally one-dimensional and the transient thermal conductive field was assumed two-dimensional in cylindrical coordinates. Thermal and optical properties were considered temperature dependent. A Gaussian distribution of the laser source (Nd-YAG with $\lambda = 1064$ nm) was chosen and a single triangular pulse was taken into account.

The comparison was done in terms of radiative characteristics, absorption function and temperature distribution in the thin films. The radiative characteristics showed a variation in time due to the temperature dependence of the optical and thermal properties. The maximum values of the absorptivity were attained at the center of the laser spot, whereas the reflectance and the transmittance had a minimum. In the back treatment case absorptivity values were higher than in the front treatment one at each radius. This leads to higher values of the absorption function and then to higher temperature values in the back treatment case than in the front treatment one.

The analysis of the two-dimensional thermal fields allowed a comparison between the FT and BT cases also with respect to the radial coordinate. This was not possible with the one-dimensional model.

The extent of the heat affected zone for the considered time period was of the same order of magnitude of the spot radius for the two techniques. It was larger in the BT case than in the FT one both at the a-Si surface and inside the a-Si layer. Finally, temperatures in the back treatment were higher than in the front treatment. For the previous reasons the back treatment was preferable as technological process in the fabrication of photovoltaic cells.

It is worth noting that a future experimental investigation on this topics is very interesting both to validate the numerical procedure and to obtain useful tools for the thermal design of the investigated processes. Moreover the proposed model could be improved by removing some of the simplifying hypothesis, such as the local one-dimensionality of the optical field.

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