

Design of amorphous carbon spectral selective coatings

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Selective coatings are the most important components of solar thermal collectors. They are fabricated usually as cermet composites, by complicated technologies. Recently, we suggested and fabricated spectral selective coatings for thermal solar collectors, based on pure hydrogenated amorphous carbon (a-C:H). However, because of the limited range of variations of the refraction index, it is difficult to achieve optimal absorber properties. In this paper, we present and discuss the design of such an absorber. We estimate the necessary absorber thickness and investigate the possibility of improving its properties by use of nanostructured aluminium substrates.

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Keywords: Thin films, Amorphous carbon, Spectral selective coating, Nanostructured substrate.

1. Introduction

Spectral selective coatings are the most important parts of solar thermal collectors. Many different coatings have been developed and are widely used today [1-3]. An ideal absorber should absorb all solar radiation and avoid losing the absorbed energy as infrared emittance. Real absorbers are, however, not perfect. Therefore, different types of spectrally selective coating are under investigation.

The main goal is to improve the solar absorption and to reduce the thermal emittance of the absorbers. There are other important properties, such as simplified fabrication technology and long lasting durability.

Recently, we succeeded in the simple fabrication of spectrally selective coatings, only by changing the deposition conditions (different bias voltages) of hydrogenated amorphous carbon films [4, 5]. In this paper, we report our efforts to design a solar absorber based on such films. Firstly, the necessary film thickness was estimated and secondly, the possibility of using a nanostructured aluminium substrate is investigated.

2. Estimation of the absorber thickness

A rough estimation of the absorber thickness d can be made using the transmittance T (Fig. 1) and the reflectance R (Fig. 2) spectra of our a-C:H films deposited on glass. From such spectra measured on thicker films, one can calculate the absorption coefficient α , αd shown

in Fig. 3 for a bias voltage of 1 kV. Here we have used the relation:

$$\alpha = \frac{1}{d} \ln \frac{(1-R)}{T}, \quad (1)$$

which is useful for thick films with $\alpha d \gg 1$. For the solar radiation maximum near 550 nm, the absorption coefficient is about $25,000 \text{ cm}^{-1}$.

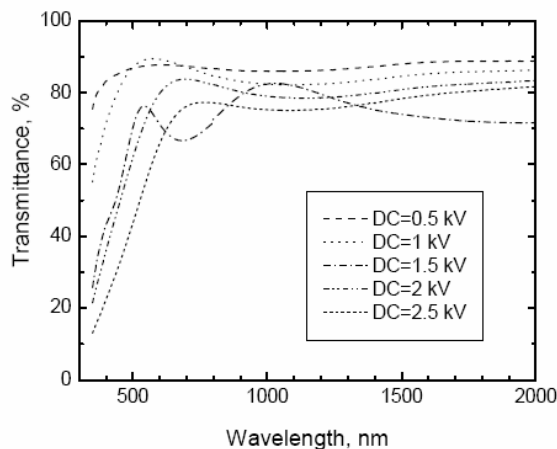


Fig. 1. The transmittances of single sublayers in the UV-VIS region.

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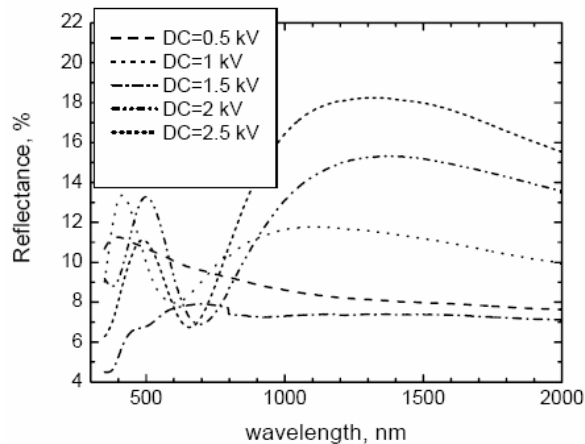


Fig. 2. The reflectance of single sublayers in the UV-VIS region.

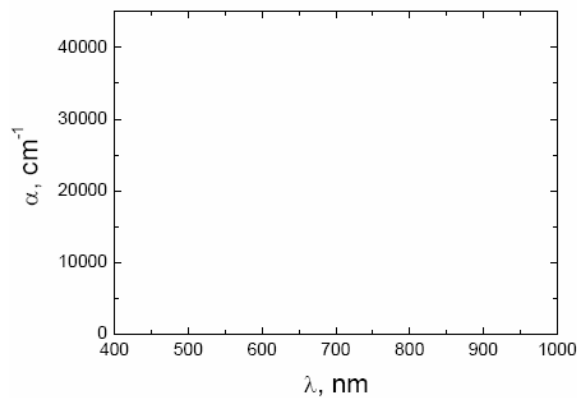


Fig. 3. The absorption coefficient of an a-C:H film deposited at DC=1kV.

Taking into account that the light is travelling twice through the absorber thickness, the estimated film thickness for 95% absorption should be about 600 nm.

3. Design of a multilayer absorber

The use of multilayer structures can improve the performance of solar absorbers. The design is based on the idea that destructive interference between adjacent layers contributes to the absorption of flat panel collectors. We developed a computer tool that takes into account the limited range of available refractive indices of a-C:H films and the technological limitations on the film thicknesses. The goal is to reduce the substrate reflection by a minimal number of layers. In what follows, we consider an Al substrate with films of complex refractive indices ($N = n - ik$) in the visible range, with n between 1.9 and 2.7 and k between 0.1 and 0.5. The films can have thicknesses from 50 to 350 nm. These values of the a-C:H film optical constants are near to experimental ones. The numerical optimization of the absorber design is based on a flexible

computer algorithm, which does not need an initial guess of the optimization parameters and does not use derivative procedures. In fact, we use a direct approach, free from the drawbacks of minimization techniques, such as the gradient search or Simplex methods. Our procedure is computer time consuming, but that is the price of making no linearization, either on the goal function, or on the model functions of the dependent variables. We define the merit function of optimization as the reduction of the substrate reflection on a wavelength-by-wavelength basis.

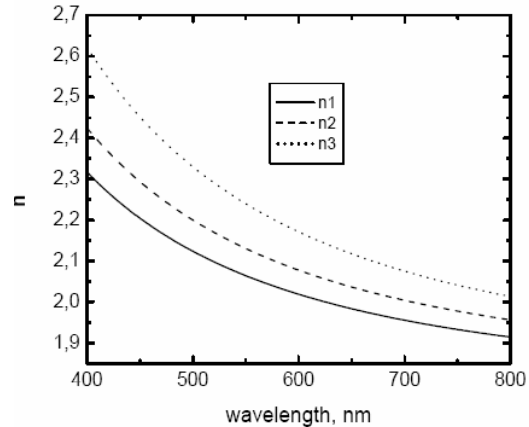


Fig. 4. Real refractive index of layers L1, L2 and L3

We reached a solution with three layers (L1, L2, L3), which will be presented below. L1 stands for the film with the lowest n , L3 – for the one with the highest n . Figs. 4 and 5 present the real and imaginary parts of N for the three layers. The design procedure makes all permutations of

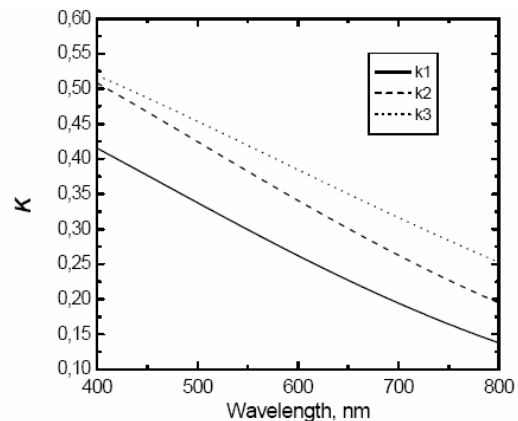


Fig. 5. Imaginary part of the refractive index of layers L1, L2 and L3, see text.

the three layers from (L1-L2-L3) to (L3-L2-L1), in order to achieve the best antireflection. In Fig.6, we show the results of the simulation for stack (L2-L3-L1), curve (1),

and stack (L2-L1-L3), curve (2). The corresponding thicknesses are (328, 83, 55) nm and (252, 88, 130) nm.

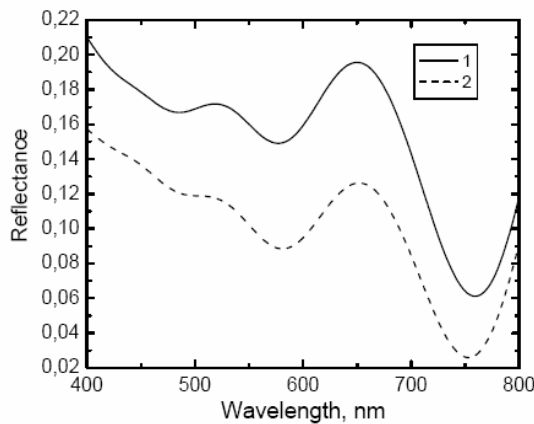


Fig. 6. Antireflection coating performance. (1) - stack (L2-L3-L1); (2) - stack (L2-L1-L3)

Of major importance is the ARC optical performance stability of the design, with respect to the experimental uncertainties in the individual layer thickness. The simulations show that our result for the (L2-L3-L1) stack is very stable. In Fig. 7 we present the dependence of the merit function on the thickness deviation of layer L3. Less than a one percent loss of the merit function is irrelevant for the spectral selective coating in the VIS. Similar results were obtained for layers L1 and L2. We have demonstrated that a-C:H films can be used for broad band antireflection multilayer structures for solar radiation absorption. Although our numerical simulations are for normal light incidence, it is known that at oblique incidence the antireflection band will shift to shorter wavelengths (nearer to 550 nm, in our case). The approach can be successfully implemented in omni-directional ARC structures with gradient index materials, etc.

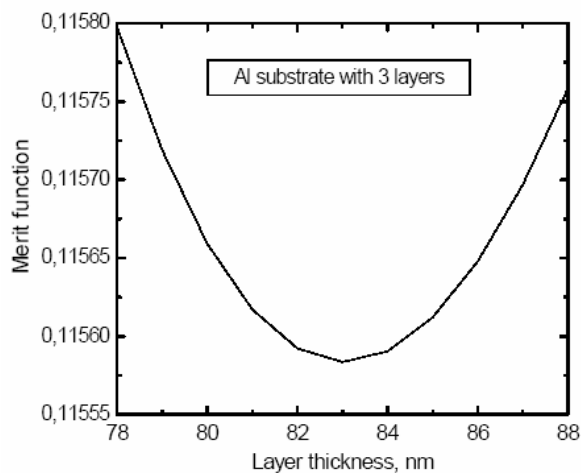


Fig. 7. Merit function dependence of L3, see text

4. Absorption enhancement by micro- and nano-structures

Solar absorbers available at present provide far from ideal black-body performance. In order to enhance further their absorption, one can use metals structured at sub-wavelength scales. Using periodic grating structures, one can achieve near-total but directionally dependent absorption. Surfaces displaying omni-directional absorption can be fabricated as random metal particle arrays, for example in black silver, Mo, Cr etc. In all such systems, the omni-directional absorption effect relies on the excitation of localized plasmons. Actually, optically selective absorber coatings in thermal solar collectors based on metal containing amorphous hydrogenated carbon (a-C:H/Metal) can be regarded as such systems.

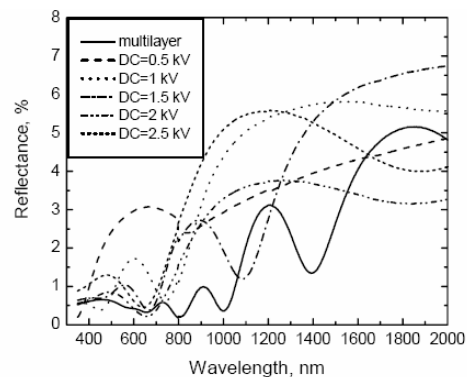


Fig. 8. The reflectance of the single sublayers and of the multilayer on the nanostructured Al in the UV-VIS region.

Other well-known techniques for the fabrication of such nanostructured surfaces are deposition of metal island films [6] and anodizing of aluminium, containing fine pores perpendicular to the surface [7]. Recently, the blackest black material was reported [8] from a vertically aligned carbon nanotube (CNT) film, with the lowest known total reflectance of 0.045 %. Although such CNT films are near perfect black-bodies, they probably will not find application in thermal solar collectors. Instead simple nanostructured absorber surfaces are promising.

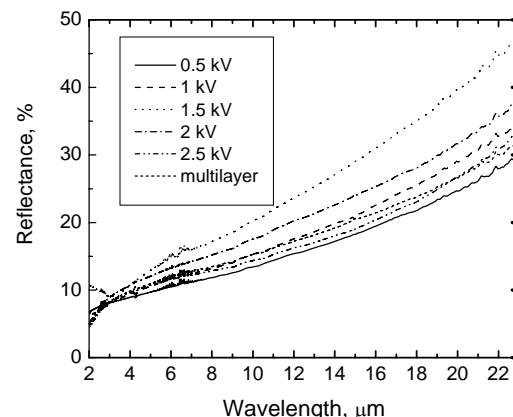


Fig. 9. The reflectance of the single sublayers and of the multilayer on the nanostructured Al, in the IR region.

In order to investigate the potential for using nanostructured absorber surfaces, we deposited our absorber films not on smooth, but on rough aluminium. Fig. 8 shows the reflectance spectrum of our a-C:H films deposited at different bias voltages and as a multilayer on the nanostructured Al substrate. In the visible range, reflection below 1 % was achieved, and below 5 % in the whole solar radiation spectrum. However, in the IR region (Fig.9), the measured reflection was not as high as it should be. Obviously more effort is needed to enhance it.

5. Conclusions

In this paper, we estimated the necessary film thicknesses of our spectrally selective coating, made from pure hydrogenated amorphous carbon. We have found that about 600 nm thick films are needed, in order to reach a solar absorptance of 0.95. Using an aluminium substrate with a nanostructured surface, one can improve this value further.

Acknowledgements

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