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High efficiency concentrated solar power plant receivers using periodic microstructured absorbing layers

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ABSTRACT

This study presents a rigorous modeling approach for 1D microstructured absorbing multi-layers for Concentrated Solar Power (CSP) receivers, taking into account both the absorption of the incident solar energy as well as the emissivity for the desired receiver temperature. Based on an optimized multilayer structure achieving high absorption, the authors demonstrate that 1D sub-wavelength period gratings can further increase the absorption and thus the efficiency of the CSP system. The C-method (Chandezon Method) is used to theoretically optimize the 1D grating profiles. An experimental demonstration of the combination of lithographic grating fabrication and absorptive layer deposition using standard silicon wafers as substrates is also presented. Experimental results show 96.5% absorption in the visible and UV range, representing an enhancement of almost 2% in comparison to non-structured coatings. Those results are promising for the design of future and competitive solar absorbers for CSP, especially since the microstructure fabrication approach can be applied to non-planar substrates such as tubes typically used as receivers in CSP plants.

1. Introduction

Surface texturing is widely used in photovoltaic (PV) technologies, enabling an improved light absorption by several optical effects. For example, by using micrometric pyramidal textures it is possible to improve light trapping by improving the phase matching, diffusing the light and increasing its mean free path in the absorbing material, allowing high absorption even in very thin cells, leading to price reduction of the panels [1–3]. Another possibility is the use of periodic gratings that diffract the light and change the incident angle on the cell's back so that the absorbent layers acts as a waveguide for a specific wavelength corresponding to the cell's gap. Surface plasmons can also be exploited by texturing the metallic back contact to produce resonant absorption with the incident wave [4–6]. In thermo-photovoltaic technology (TPV), where the idea is to reemit the thermally captured energy within a specific IR wavelength adapted to the receptor, metallic structures have been used to produce surface plasmon effects on the emitter part, avoiding losses due to light emitted at lower energy than the cell's gap [7–9].

Contrary to PV and TPV, surface texturing is up to now less commonly used for concentrated solar power systems (CSP [10]), which use optical elements to focus the sunlight on an absorber, creating heat that powers conventional heat engines, which in turn produce electrical energy. The most common setups (parabolic-troughs, linear Fresnel reflector) reach temperatures of about 250–450 °C [11]. At this working temperature, thermal losses are mainly radiative. Thus, there is a viable interest in improving the spectral absorption characteristics of the receiver by optimizing its interface with the surrounding medium in order to achieve high solar absorbance and low thermal emittance in the infrared domain (IR) beyond 2450 nm. The use of multilayer coatings has been widely investigated [12–14], representing the most commonly used solution to the problem. Texturing the surface is often aimed at producing cost effective and thermally stable absorbers by improving the intrinsically absorbent behavior of refractory metal substrates (often tungsten) [15,16]. One advantage of bulk metals with a textured surface with regard to multilayer coatings is their superior thermal stability [17,18]. Textured surface absorbers can take advantage of the effects of phase matching and optical index gradation, requiring thus not necessarily a strictly periodic structure, which allows the use of cost effective technologies on large surfaces, like chemical etching treatment, nanowire growing by thermal treatment or laser sintering [19,20]. At a

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higher scale, millimeter pyramidal structures can improve the directional selectivity. For CSP applications most of the solar irradiance reaches the absorber under normal incidence, whereas thermal emissivity is a spherical property. Deep macroscopic structures enable to take advantage of this situation by increasing absorption at normal incidence and reducing emissivity at glazing angle [21].

The current paper reports on the combination of surface texturing and thin multilayer coatings, leading to a further enhancement of the spectral selectivity of CSP absorbers. This is the main topic of the ASTORIX (High Temperature Oxido-Resistant mIcroteXtured Solar Absorbers) project in the framework of French National Agency for Research (ANR), with the participants PROMES laboratory and industrial partner HEF being responsible for the thin layer deposition, and Hubert Curien laboratory providing the theoretical modeling of the absorbing layers with periodic micro-textured diffraction gratings, as well as the lithographic grating fabrication. It has been demonstrated that such multi-scale structures can efficiently improve solar absorption [22]. Sergeant et al. [23,24] have modeled the optical behavior of multilayer absorbers deposited on sub-wavelength periodic gratings and shown an improvement of the spectral selectivity. In contrast to stochastic patterning in the range of the considered wavelength, gratings have well defined periodic structures, and well known wave-optical methods like the Chandezon method (C-method) and Rigorous Coupled Wave Analysis (RCWA) exist to simulate their reflectance and absorption. [25,26].

For the presented system of 1D gratings associated with multi-layer coatings the optical behavior was modeled using the Chandezon method. The simulations allowed finding optimal parameters for the layer thicknesses, period and depth of the grating to reach the highest photo-thermal efficiency for a working temperature of about 300 °C and a CSP concentration ratio equal to 50. In order to validate the theoretical model and the obtained theoretical results, a demonstrator has been realized, using a silicon wafer as substrate. The gratings were fabricated in photoresist using 2-beam interference lithography, followed by the deposition of four thin layers using different physical vapor deposition (PVD) techniques.

2. Optical modeling

2.1. Goal and efficiency calculation method

This paper is aimed at the development of absorbers for LFR systems (Linear Fresnel Reflector) at a working temperature of T_a=300 °C with a concentration ratio of the sun's radiant flux of X=50. The efficiency η is estimated using Eq. (1), where σ is the Stefan-Boltzmann constant, E the solar luminance at ground level (in W/m^2), T_O the ambient temperature of the environment, α_s is the solar absorption and ε is the thermal emissivity at working temperature.

$$\eta=\alpha_s-\frac{\varepsilon(T_a)\sigma}{XE}\times(T_a^4-T_0^4) \tag{1}$$

Solar absorption is calculated from hemispherical reflectance using Eq. (2), where G is the ASTM-G173 (American Society for Testing and Materials) direct + circumsolar solar spectrum at A.M 1.5 (Air Mass) and R is the reflectance.

Emissivity at 300 °C is evaluated by Eq. (4) using Kirchhoff's law (3). In Eq. (4), P is the black body spectrum defined by Planck's law.

$$\alpha_S=\frac{\int_0^\infty[1-R(\lambda,T_a)]\cdot G(\lambda)\cdot d\lambda}{\int_0^\infty G(\lambda)\cdot d\lambda} \tag{2}$$

$$\varepsilon(\lambda,T)=\alpha(\lambda,T) \tag{3}$$

$$\varepsilon(T)=\frac{\int_0^\infty[1-R(\lambda,T_a)]\cdot P(\lambda,T)\cdot d\lambda}{\int_0^\infty P(\lambda,T)\cdot d\lambda} \tag{4}$$

Due to the high concentration ratio the absorption has a higher impact on the efficiency than the emissivity, which is important for the optimization process of the absorber [27].

2.2. Description of the modeled structure

The presented selective coating is made of four optimized layers. The bottom layer is a compound of aluminum and plays the role of an IR reflector. The next two layers constitute a tandem absorber made from $\mathrm{Ti_xAl_yN_z}$. Those two layers have different nitrogen contents leading to a refractive index gradation. The layer closer to the substrate behaves more like a metal due to a lower nitrogen content. The closer the layers are to the metallic substrate, the higher is their refractive index. This structure has been optimized to achieve high absorption. On top, an $\mathrm{Al_2O_3}$ antireflective layer enhances the transmission of the solar spectrum towards the absorptive layers.

The absorbing layers described above have been deposited on a unidirectional grating with a trapezoidal shape. The substrate holds the structure. This structure has been modeled using the C-method as implemented in the commercial software MC GRATINGS©. For this method the shape of the surface and each interface of the multilayer is defined using Fourier series. Solving the Maxwell equations in this system allows simulating the reflectance of all propagating diffraction orders. As a first approximation the layers are assumed to be conformal, following the shape of the underlying grating (Fig. 1).

2.3. Optical index and multilayers modeling

The optical behavior of the TiAlN material is modeled by the association of a Drude model with 3 Lorentz oscillators. The Drude model describes the interaction of light with free electrons and Lorentz oscillators take into account lattice vibration and valence electrons oscillations [28]. To calculate the TiAlN optical index, Eq. (5) has been used, where ε is the complex dielectric constant, ε_∞ is the high frequency component of the dielectric constant, ε_s is the value of the static dielectric function at zero frequency, ω_p is the plasma frequency, ω_t is the resonance frequency of the oscillator corresponding to the absorption peak, Γ_d is the damping factor for the Drude term, Γ_0 is the damping factor of each Lorentz oscillator, ω_{Oj} are the resonant energies of Lorentz oscillators, f_{Oj} are the oscillator's strength and γ_j are the broadening parameter at each peak energy of the Lorentz oscillators.

$$\varepsilon(\omega)=\varepsilon_\infty+\frac{(\varepsilon_s-\varepsilon_\infty).\omega_t^2}{\omega_t^2-\omega^2+i.\,\Gamma_0.\,\omega}+\frac{\omega_p^2}{-\omega^2+i.\,\Gamma_d.\,\omega}+\sum\nolimits_{j=1}^{2}\frac{f_j\,.\,\omega_{0j}{}^2}{\omega_{0j}{}^2-\omega^2+i.\,\gamma_j.\,\omega} \tag{5}$$

In order to deduce the refractive index, experimental reflectance curves of a monolayer have to be fitted to the described model (Fig. 2). To this end, monolayers of different TiAlN compositions have been deposited on silicon wafers, with the edge of the wafer being masked using Kapton© in order to produce a step. Layer thickness was then measured with a profilometer to estimate the deposition rate.

The result of the fitting is a refractive index of the TiAlN layer with high nitrogen concentration of 2.41 and an extinction coefficient of 0.35 at 550 nm. For the low nitrogen concentration layer, the behavior

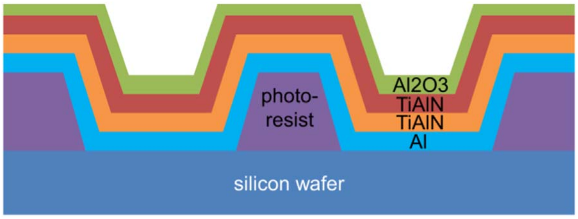

Fig. 1. Sketch of modeled surface structure.