CHEMICAL ENGINEERING TRANSACTIONS

VOL. 101, 2023

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Paolo Ciambelli, Luca Di Palma

ISBN 979-12-81206-00-7; **ISSN** 2283-9216

DOI: 10.3303/CET23101002

$W/W-SiCH/TaO_xN_y$ Multinanolayers for Concentrated Solar Power

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Absorbers for concentrating solar power plants require materials that are resistant to high temperatures and spectrally selective, i.e., highly absorbent in the visible and near infrared range and low-emissive in the infrared range. To improve the absorbing power of the receivers in concentrating solar power plants, an optical end coating based on tantalum oxynitride can be deposited on an absorbing bilayer based on metal and ceramic materials. Antireflective TaO_xN_y coating can maximize the transmission of solar radiation to the $W/W-SiCH$ bilayer absorber material which has been previously studied and ensure a good thermomechanical resistance of the whole coating. For this study, TaO_xN_y are deposited by reactive sputtering technique. Their chemical composition is investigated by Ion Beam Analysis which shows compositions ranging from tantalum oxide to tantalum nitride depending of the gas flow rate. Optical properties are determined by ellipsometry and UV-Visible spectroscopy. The microstructure determined by the Pair Distribution Function (PDF) reveals a mixture of TaN, $TaON$ and Ta_2O_5 phases.

1. Introduction

Concentrating solar power plants are booming as a result of the need to produce clean electricity. Numerous studies on the subject have been carried out (Wang Cong et al., 2021), including those on solar receivers. The coatings used for the absorbers must be spectrally selective, i.e. they must be able to modify the coated surface in such a way that it can absorb a maximum amount of solar radiation in the solar visible and near infrared range and emit very low radiation in the thermal infrared range. These selective absorbers must also satisfy other criteria such as high temperature resistance to air and thermomechanical resistance. One interesting solution is to insert them between a metallic underlayer that acts as an infrared reflector to minimize radiative losses and an antireflective top layer that maximizes the transmission of solar radiation. In their study Li et al. (2013) presented a SiO_2 and TiO_2 or ZrO_2 type stack that increases the transmission by more than 3% over a range of 300 to 1000 nm. This transmission can reach 99% in the case of nanostructuration for a wavelength close to 600 nm depending on the grain size. Most of the absorbers existing in the literature have good solar performance and a high temperature resistance of up to 650 °C under vacuum (Bermel et al., 2012)). Increasing the operating temperature (500°C<T<700°C) and using solar receivers in the air and not in vacuum would improve the efficiency of solar power plants and reduce their cost. For that reason, we will focus on tantalum oxynitride antireflective coatings deposited on $W/W-SiCH$ absorbing layers that we have studied previously (Danielle Ngoue, 2017; Diop et al., 2023). Within the family of oxides, tantalum pentoxide, whose chemical formula is Ta_2O_5, has interesting optical properties that allow it to be used as an antireflective coating. Work by Rubio et al. (1983) showed that this coating increased the efficiency of silicon from 9.5% to 12.9% when deposited as an antireflective coating with a refractive index close to 2 in the visible range. In the nitride family, work (Wang et al., 1998) has shown that nitrogen incorporated into tantalum layers can be used to obtain TaN as a diffusion barrier.

Paper Received: 7 January 2023; Revised: 29 March 2023; Accepted: 4 June 2023
Please cite this article as: Diop A., Soum-Glaude A., Bousquet A., Sauvage T., Thomas L., Tomasella E., 2023, W/W−SiCH/Ta O x N y multinanolayers for Concentrated Solar Power , Chemical Engineering Transactions, 101, 7-12 DOI:10.3303/CET23101002

Due to its good mechanical properties, tantalum nitride can be used as a durable protective coating. Tantalum oxynitrides, with the chemical formula TaO_xN_y, are a good compromise between oxides and nitrides in that their properties are halfway between those of nitrides and oxides.
In this work, TaO_xN_y thin films were deposited by reactive magnetron sputtering of a tantalum target in a plasma of argon at a fixed flow rate, dioxygen and dinitrogen at variable flow rates. They were then characterised to determine their chemical composition using Ion Beam Analysis techniques and their optical nature using spectroscopic ellipsometry measurements. A structural study was also carried out by Pair Distribution Function (PDF). Finally, optical simulations carried out using an in-house software package was used to show the improvement in the optical properties of the $W/W-SiCH$ absorbing layer when a TaO_xN_y layer is deposited on top.

2. Experimental setting

2.1 Coatings synthesis

TaO_xN_y layers were deposited in a plasma in a vacuum chamber provided by PLASSYS, which can accommodate two magnetron cathodes, each connected to a SEREN radio frequency generator providing a maximum power of 300 W. It is also equipped with a rotating and heating substrate holder, which can also be polarised by radio frequency. The initial pressure in the deposition chamber is of the order of 10^{-6} mbar. The substrates on which the materials are deposited are cleaned by RF plasma for 10 min under 20 sccm argon flow. During deposition, the pressure in the reactor is about 1 Pa (10^{-4} mbar). The target used is 99.99% pure tantalum with a 3 inches diameter. According to the type of material characterization, the layers were grown on silicon (N-type, P-doped, 2-sided polished), quartz (transmission range: 0.185~3.50 µm) or glassy carbon (1-sided polished, resistivity: 400 µΩ.cm) substrates. The argon flow rate is fixed at 15 sccm and those of N_2 and O_2 are variable. We denoted RF the flux ratio which corresponds to the ratio between the flow rate of O_2 and the total flow rate of reactive gases (O_2+N_2) ($RF = \frac{\Phi(O_2)}{\Phi(O_2+N_2)}$). With $\Phi(O_2 + N_2) = 2\ sccm$. Table 1 presents the different samples obtained according to the reactive gas flow rates and the measured thickness.

Table 1 : Samples obtained according to the reactive gas flow rates

Samples	$\phi(N_2)$	$\phi(O_2)$	Thickness (nm)
RF0	2 sccm	0 sccm	184
RF0.4	1.2 sccm	0.8 sccm	194
RF0.7	0.5 sccm	1.5 sccm	194
RF1	0 sccm	2 sccm	110

2.2 Materials characterizations

RBS (Rutherford Back Scattering) was used to determine the depth profile of chemical elements in the material, by bombarding the sample placed in a vacuum chamber with an alpha beam (${}^4_2He^+$) of 2 MeV energy. RBS analyses were completed by NRA (Nuclear Reaction Analysis) and ERDA (Elastic Recoil Detection Analysis) analyses to get more precise information on the chemical composition of the materials, especially in light elements contents. The depth profiles were extracted from IBA spectra by using SIMNRA software (Mayer, 1999) with SigmaCalc cross section (Gurbich, 2016) for NRA and ERDA. These IBA techniques were carried out using the Pelletron accelerator of CEMHTI laboratory (EMIRA 2022). A Jobin-Yvon Uvisel ellipsometer was used to determine the spectral refractive indices n and extinction coefficients k of our materials. Its incident beam (angle of incidence 70°) comes from a Xenon lamp. The device allows studies to be carried out over a range from 0.49 to 4.79 eV (258.8 nm to 2101.4 nm). After measurements, a modelling step by Tauc Lorentz (Gaillet, 2018) using the DeltaPsi 2 software (HORIBA 2016) was applied to determine n and k. Transmission measurements were performed with a Perkin Elmer UV-Visible spectrometer scanning wavelengths from 200 nm to 900 nm. It is a dual beam spectrometer equipped with two light sources: a deuterium arc lamp for wavelengths below 350 nm and an incandescent lamp for visible wavelengths. The structural characterization was determined by PDF with a PANalytical X'Pert Pro diffractometer with Bragg-Brentano θ-θ geometry) from PHILIPS equipped with a copper anticathode ($K\alpha_1/K\alpha_2$) and a solid X'celerator detector that covers an angular range of 2.122°. The data are normalised and Fourier transformed using PDFgetX3 software and signal modelling was performed using PDFgui software.

2.3 Optical simulations

Optical simulations are performed with COPS software which is a Solar Performance Optimization Code developed under Scilab 5.5.2 in the framework of the thesis of A. Grosjean (Grosjean et al. 2021) at the PROMES laboratory. It allows to evaluate the solar performances of nanometric materials via the calculation of the spectral reflectance R(λ), the spectral transmittance T(λ) to then deduce the spectral absorptance A(λ) according to the law of conservation of energy. It supports the modelling of spectral and solar properties of thin films but also the optimization of coating variables (layer thicknesses and compositions) to obtain the best performance of the considered materials. The program is based on the calculation of Fresnel coefficients by the transfer matrix method, to determine the global reflected and transmitted power and the parameters described above.

3. Results and discussions

3.1 Chemical composition

The chemical composition presented in Figure 1a showed that tantalum varies little with the flux ratio RF, while oxygen ranges from 20% to 70% and nitrogen varies between 0 and 45%. The traces of nitrogen observed for RF1, sample elaborated with 0 sccm of N_2, can be attributed to residues present in the reactor before deposition. For RF0, the oxygen rate above 20% can be explained by a strong oxidation after deposition. Indeed, the hydrogen rate of this sample is higher than for the other samples, according to Figure 1b. This would mean that this sample is very unstable. The stoichiometries obtained cover the range between those of TaO_xN_y and Ta_2O_5.

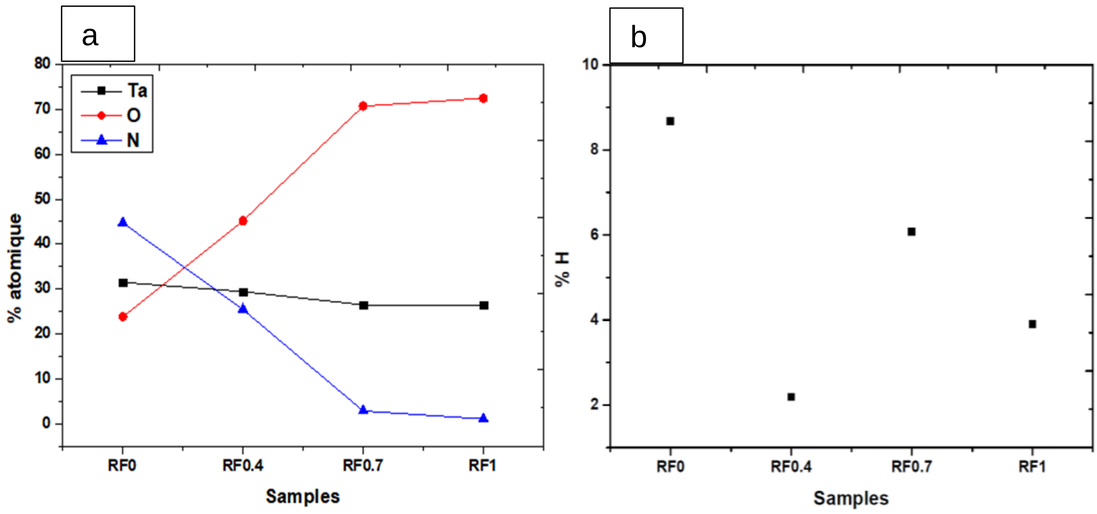

Figure 1 : Atomic contents (a) according to RBS and NRA, and hydrogen percentage (b) according to ERDA, depending on the flux ratio RF

3.2 Optical properties

Figure 2 shows the refractive indexes and extinction coefficients of the films at a wavelength of 632.8 nm. The RF0 sample is opaque, with a value of *k* near 1.25 and has the highest value of *n* (3.45). As RF increases, *n* and *k* decrease, making the samples transparent. This is due to the incorporation of oxygen into the films in that increasing RF is equivalent to increasing the oxygen content, as shown in the chemical composition. The values obtained for RF1 are very close to those obtained by Banakh et al. (2006) for Ta_2O_5 (*n* = 2.5 and *k* = 0).
The transmission (Figure 3a) and optical gap E_g (Figure 3b) curves were obtained by UV-Visible spectrophotometry. The maximum value of the transmission at 632.8 nm is 60%. This value indicates that RF0 has an oxide phase which affects the optical properties as nitrogen-rich materials have a transmittance of about 45% at 633 nm. From RF0.4, the materials are transparent, reaching a transmittance of more than 90% for RF1, as for Ta_2O_5 like materials. Eg increases with increasing RF due to the substitution of N atoms by O atoms in the growing film. For RF0, E_g is equal to 1.8 eV, which is higher than TaN values (Zoubian et al., 2011). E_g reaches a maximum of about 4.1 eV for RF1, a value close to that obtained by Banakh et al. (2006) for Ta_2O_5.

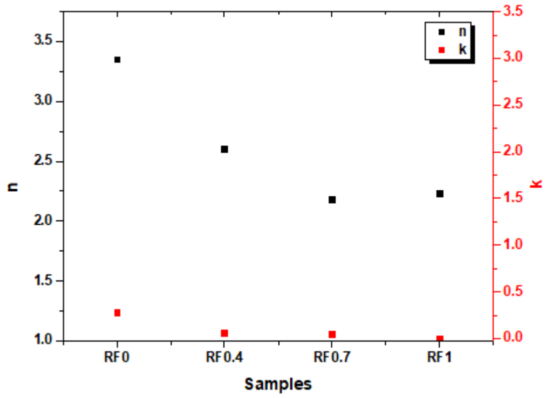

Figure 2 : Refractive index (n) and extinction coefficient (k) at 632.8 nm depending on the flux ratio RF

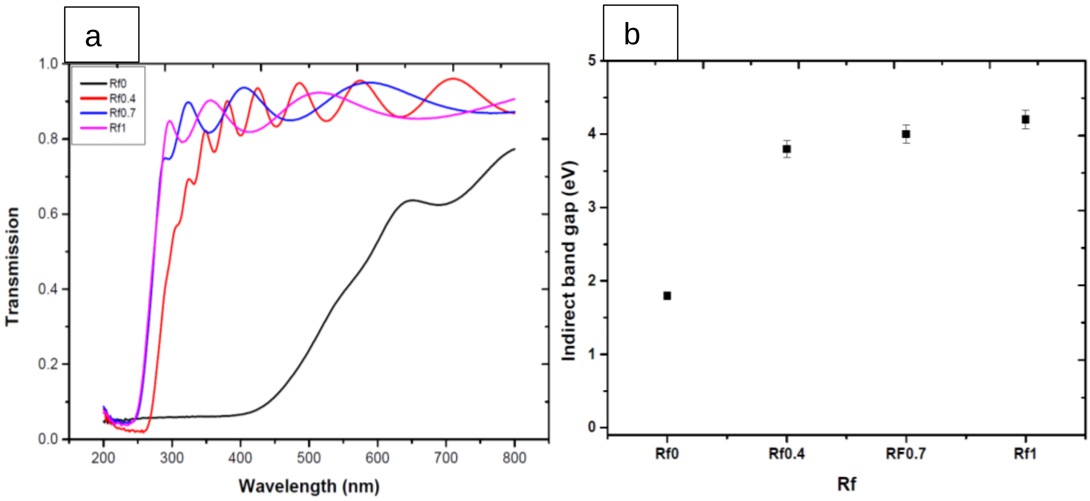

Figure 3 : Optical transmittance (a) and optical band gap (b) depending on the flux ratio RF

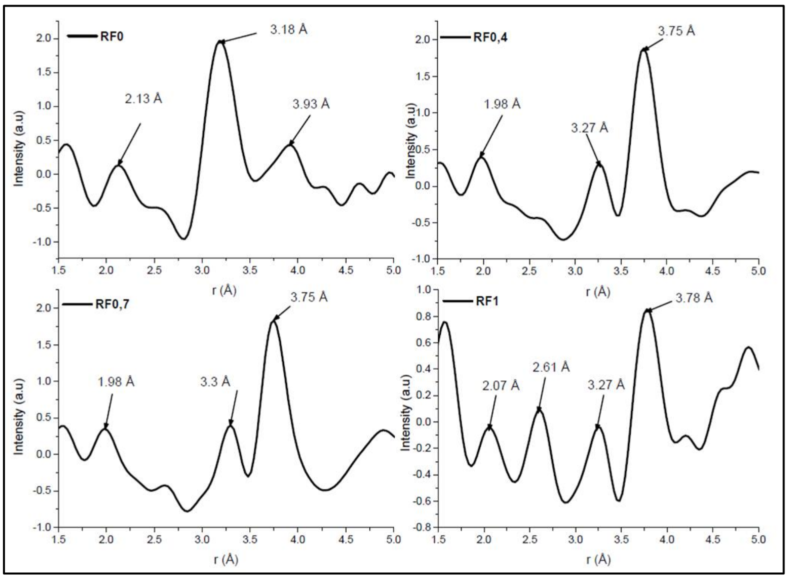

Figure 4 : PDF spectra showing distance and coherence domains of samples depending on the flux ratio RF

3.3 Structural characterization

The structural characterization is performed by PDF. The spectra obtained are presented in Figure ***4***. For sample RF0, we observed Ta-N bonds at 2.13 Å and 3.94 Å which may result from the Ta_3N_5 phase respectively. A Ta-Ta bond from the Ta_3N_5 phase was also observed at 3.18 Å. This suggests that this sample is close to Ta_3N_5. For samples RF0.4, RF0.7 and RF1, the Ta-O, O-O and again Ta-Ta bonds seem to indicate that this is a mixture of Ta_2O_5 and TaO_xN_y phases. This is consistent with the stoichiometries obtained from the chemical analysis. The coherence domains of the materials are very limited, so the indexation of the peaks was done on a reduced range of distances. When the RF increases, the size of the domains decreases, which means that by substituting nitrogen by oxygen, one tends towards an amorphous compound.

3.4 Optical simulations

To perform optical simulations, we used the optical indexes measured by ellipsometry. Figure 5 shows a simulation of the spectral reflectance of a W/W-SiCH bilayer on silicon (red curve), and that of a trilayer consisting of the same bilayer architecture on which a TaO_xN_y RF0.7 layer was added (blue curve). The optical indexes of the W-SiCH absorbing layer were obtained from a sample synthesized at the PROMES laboratory, by sputtering a W target in a plasma of argon and TetraMethylSilane (TMS) on a silicon substrate previously heated to 350°C, and using 850 W of microwave power to assist the reactive sputtering (Danielle Ngoue, 2021; Diop et al., 2023). The TMS flow rate used was 4.5 sccm for a total gas flow rate in the reactor of 25 sccm. The yellow curve represents the solar spectrum, and the brown dashed curve represents the black body emission spectrum at 500°C. The addition of the antireflective layer reduces spectral reflectance, especially in the visible and near infrared range. Such modification of the reflectance has an impact on the optical properties, in particular on solar absorptance (Grosjean et al., 2018). This sample would thus make it possible to increase the rays transmitted to the absorbing layer and consequently to increase its absorbing capacity.

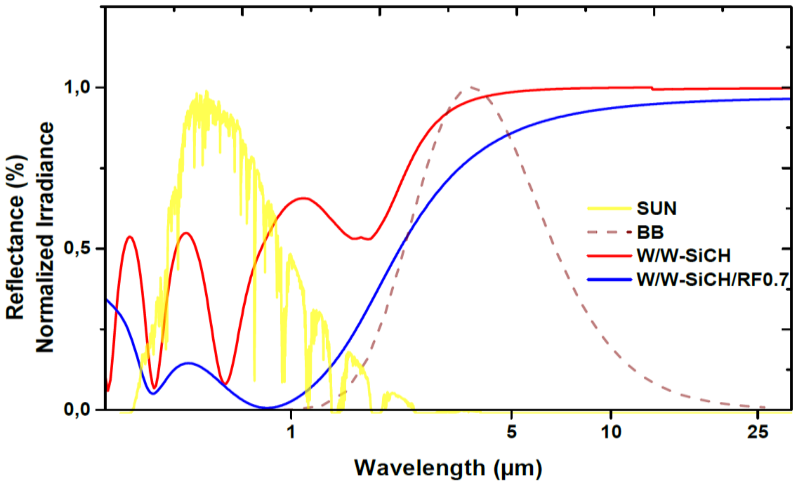

Figure 5 : Optical simulation of an absorbing layer and a stack of the absorbing layer and an additional antireflective layer

4. Conclusions

TaO_xN_y thin films were deposited by reactive magnetron sputtering of a tantalum target in an Ar/N_2/O_2 plasma. Chemical composition according to RBS reveals stoichiometries ranging from TaO_xN_y to Ta_2O_5, depending on the flux ratio RF. Films with high oxygen content show high transparency, according to optical measurements performed by ellipsometry and UV-Visible spectroscopy. The optical band gap is ranging from 1.8 to 4.1 eV and increases with increasing RF (i.e., oxygen content). The optical simulations show that the addition of the RF0.7 antireflective layer, from the tantalum oxynitride range, on the W/W-SiCH absorbing layer increases the solar flux absorption by reducing reflectance in the visible range, due to the increased transmittance of the antireflective layer. This opens several study perspectives for improving the performance of solar radiation harvesting in concentrated solar power plants.

Acknowledgments

This work was financed by the French National Agency for Research (ANR) as part of the NANOPLAST project (award n°ANR-19-CE08-0019, nanoplast-project.cnrs.fr) and of the French “Investments for the future” program managed by ANR under contract ANR-10-LABX-22-01-SOLSTICE. The authors thank B. Diallo, C. Tavio-Geho, O. Wendling, A. Bellamy, A. Grosjean, and all the technical partners for their involvement.

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