

Article

Accurate Design of Solar Selective Absorber Based on Measured Optical Constants of Nano-thin Cr Film

Zheng-Yong Wang ^{1,†}, Er-Tao Hu ^{1,*,†}, Qing-Yuan Cai ², Jing Wang ³, Hua-Tian Tu ⁴, Ke-Han Yu ^{1,*}, Liang-Yao Chen ⁴ and Wei Wei ¹

- ¹ College of Electronic and Optical Engineering & College of Microelectronics, Nanjing University of Posts and Telecommunications, Nanjing 210023, China; 1218022719@njupt.edu.cn (Z.-Y.W.); iamww@fudan.edu.cn (W.W.)
- ² Shanghai Institute of Technical Physics, Chinese Academy of Sciences, Shanghai 200083, China; qycai@mail.sitp.ac.cn
- ³ Department of Basic Education, Tongda College of Nanjing University of Posts and Telecommunications, Yangzhou 225127, China; wangjing@nytdc.edu.cn
- ⁴ Department of Optical Science and Engineering, Fudan University, Shanghai 200433, China; 16110720002@fudan.edu.cn (H.-T.T.); lychen@fudan.ac.cn (L.-Y.C.)
- * Correspondence: iamethu@njupt.edu.cn (E.-T.H.); kehanyu@njupt.edu.cn (K.-H.Y.); Tel.: +86-25-8586-6131 (E.-T.H. & K.-H.Y.)
- + The first two authors contributed equally to this work.

Received: 29 August 2020; Accepted: 28 September 2020; Published: 30 September 2020



Abstract: Solar selective absorbers have significant applications in various photothermal conversion systems. In this work, a global optimization method based on genetic algorithm was developed by directly optimizing the solar photothermal conversion efficiency of a nano-chromium (Cr) film-based solar selective absorber aiming to work at the specified working temperature and solar concentration. In consideration of the semi-transparent metal absorption layer employed in multilayered solar selective absorbers, the optical constants of ultrathin Cr film were measured by spectroscopic ellipsometer and introduced into the optimization process. The ultrathin Cr film-based solar selective absorber was successfully designed and fabricated by the magnetron sputtering method for the working temperature at 600 K and a solar concentration of 1 Sun. The measured reflectance spectra of the sample show a good agreement with the numerical simulations based on measured optical constants of ultrathin Cr film or literature data exhibit a large discrepancy with the experimental results. It demonstrates the significance of considering the actual optical constants for the semi-transparent metal absorption layer in the design of nano-metal film-based solar selective absorber.

Keywords: solar selective absorber; photothermal conversion efficiency; genetic algorithm; design; ultrathin Cr film; optical constants

1. Introduction

Solar-thermal conversion systems, which can convert abundantly available solar energy into heat, have been extensively studied in the past decades due to its advantages of high energy-conversion efficiency, simple device structure, and appealing energy storage functionality. It has a large variety of practical applications such as solar heating, concentrating solar power, solar thermoelectrics, solar thermophotovoltaic, solar seawater desalinization, and so on [1–6]. The critical element of a solar thermal conversion system is the solar selective absorber which can simultaneously maximize solar absorption over the wide solar radiation wavelength range, while minimizing the parasitic heat losses due to blackbody radiation in the infrared spectral region [2,3].



2 of 11

Solar absorptance α and thermal emittance ε are the most commonly quoted physical criteria to characterize the performance of solar selective absorber [7]. In terms of the fraction of sunlight converted to heat by the solar selective absorber, then at a particular temperature *T* and solar optical concentration *C*, the solar photothermal conversion efficiency (PTCE) η_t is defined as [3,8–10]: $\eta_t = B\alpha - \frac{\varepsilon \sigma T^4}{Cl}$, where σ , *B*, and *I* are the Stefan–Boltzmann constants, the transmittance of glass envelope, and solar radiation intensity (AM1.5 solar radiation spectrum), respectively.

Semi-empirical approach [11,12], traversing method [1], admittance locus method [13], and commercial software [14–18] have been employed to design the multilayered solar selective absorber. A large variety of multilayered solar selective absorbers with different constituent materials and configurations have been proposed such as HfO₂/Mo/HfO₂/Mo [19,20], SiO₂/Si₃N₄/W/SiO₂/W [5], Al₂O₃/Al₂O₃-W/Al₂O₃-WTi/Al₂O₃/W [1], Al₃₄O₆₂N₄ /AlN/ZrN/AlN/ZrN/Zr_{0.2}Al_{0.8}N/Cu [15], SiO₂/Cr/SiO₂/Cr/SiO₂/Cu [2,12,21], 11 layers of W, TiO₂, and MgF₂ [22], to make solar absorptance higher than 95% with lower thermal emittance being achieved. Various metal/metal oxide-based tandems were also simulated to obtain promising solar selective properties suitable for further experimental fabrication [18,23]. However, most of them are limited to just optimize solar absorptance and thermal emittance [2,10,24–26], rather than focusing on the solar PTCE, which is more practical for solar selective absorbers working at a particular temperature and solar concentration [27–29]. To mitigate this situation, the particle-swarm optimization method [5] and genetic algorithm [9] have been developed to directly optimize the PTCE of the solar selective absorber. However, in their simulations, the optical constants were obtained from Palik, corresponding to the bulk optical materials [18,30]. In fact, film thickness of the metal absorption layer used in multilayered solar selective absorber was always smaller than 30.0 nm [2,11–13,21,31], smaller than its electron mean free path, resulting in a large difference in its optical constants compared with that of the bulk counterpart [32,33]. Hence, to accurately design the solar selective absorber, optical constants of the ultrathin metal absorption layer must be measured in advance [5].

In this work, a global optimization method based on the characteristic transfer matrix method and the genetic algorithm was developed to optimize the solar PTCE of the multilayered solar selective absorber. A six-layer selective solar absorber based on ultrathin Cr film was designed and fabricated to validate the proposed program. The optical constants of ultrathin Cr film were particularly measured in advance and introduced into the optimization process.

2. Numerical Design

The six-layered film structure investigated in this work is schematically presented in Figure 1a, with SiO₂ and Cr layers alternatively stacked on top of the optically thick Cu reflection layer (>100.0 nm). The bottom Cu reflection layer is thick enough to ensure a zero light transmittance of the film structure. In addition, due to its high light reflectance in the long-wavelength range, the thermal emittance of film structure can be reduced as well. The top-most SiO₂ layer serves as the antireflection layer and the protection layer, while the lower SiO₂ layers are used as the phase-matching layers [12]. The absorption of incident solar light can be enhanced due to the intrinsic absorption of the semi-transparent Cr layer when they are repeatedly reflected between the Cr and Cu layers, which is known as destructive interference effect [12,34]. The interference enhancement behavior of the incident light on the multilayer metal/dielectric film structure has been particularly investigated in the work [19].

The proposed six-layered film structure can be considered to be isotropic and homogenous. Thus, its reflectance spectra can be obtained by using the transfer matrix method (TMM) [9,35]. The optical constants for Cu and SiO₂ were obtained from Palik and Skowronski [30,36]. For Cu, it has been proved that using the optical constants from Palik can well produce the reflectance spectra of the fabricated Cu sample [37]. For the dielectric material of SiO₂, its optical constants tend to be almost invariant when its film thickness increases to about several nanometers [38]. Nevertheless, due to the thickness-dependent optical constants of ultrathin metal films, optical constants of the semi-transparent Cr layer were obtained from the spectroscopic ellipsometry measurements [32,33].



Figure 1. (a) Schematic six-layered SiO₂/Cr film structure, (b) convergence curve of the six-layered SiO₂/Cr film structure at the working condition of 600 K and 100 Suns.

For solar selective absorber with a relatively smooth surface, it can be regarded as a mirror surface with negligible diffuse reflection. Then, α can be directly deduced from the near-normal specular reflectance spectra, which can be expressed as [2]:

$$\alpha = \frac{\int_{\lambda_1}^{\lambda_n} [1 - R(0, \lambda)] d\lambda}{\int_{\lambda_1}^{\lambda_n} L_{sun}(\lambda) d\lambda}$$
(1)

where λ and $R(0,\lambda)$ represent the wavelength and specular reflectance spectra under the near-normal incidence condition, respectively. $L_{sun}(\lambda)$ is the spectral intensity of solar radiation at each wavelength. The integrated wavelength range is from 250 to 3000 nm to cover nearly the entire solar radiation wavelength range.

According to the law of Planck's blackbody radiation, the sample heated by sunlight will thermally re-radiate the energy into the half-space above its surface. The hemispherical thermal emittance can be given by [9,31]:

$$\varepsilon_{thermal}(T) = \frac{2\int_0^{\pi/2} \int_0^\infty E(T,\lambda) [1 - R(\theta,\lambda)] \cos \theta \sin \theta d\lambda d\theta}{\int_0^\infty E(T,\lambda) d\lambda}$$
(2)

where θ and $E(T,\lambda)$ are the incident angle and Planck's blackbody radiation spectra at temperature *T*. In this work, the integrated wavelength was from 250 to 25,000 nm, which is enough to account for the blackbody radiation spectra region.

Then, solar PTCE can be obtained according to $\eta_t = B\alpha - \frac{\varepsilon \sigma T^4}{CI}$. In this study, σ and B are set to be $5.67 \times 10^{-8} \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}$ and 1, respectively. For the unconcentrated solar case, $I = 1000 \text{ W/m}^2$ (1 Sun).

To design the six-layered solar selective absorber working at a particular temperature and solar concentration, each layer's thickness was optimized to maximize the solar PTCE of the multilayered solar selective absorber by the genetic algorithm (GA) [9,39]. GA is a well-known method to generate high-quality solutions for optimization and search problems which is based on the natural biological evolution process. As a globally random search method, GA has the advantages of independent of the gradient information of the objective function, strong robustness, suitable for parallel processing, and so on. A group of film thicknesses of the six-layered film structure was assigned as an individual. The solar PTCE was defined as the evolution function. The crossover and mutation probability were fixed at 0.7 and 0.2, respectively in the optimization process. After the careful test, 200 initial populations and 150 generations can ensure the convergence of the optimizations. Figure 1b shows the convergence curve of the six-layered chromium-silica film structure aiming to work at 600 K and 100 Suns. As can be seen, after 150-generation's evolution, the solar PTCE of the 6-layered film structure will have a negligible variation.

3. Experimental Details

The Cu, Cr, and SiO₂ films were deposited by a magnetron sputtering system (INFOVION, Seoul, Korea) with the commercially available high-purity targets (\geq 99.99%, 3 inches in diameter). Si (100) wafer was used as substrate, which was ultrasonically cleaned sequentially in acetone, alcohol, and deionized water for 10 min, respectively, and dried by nitrogen flow before they were placed into the chamber. Cu and Cr were deposited by direct current (DC) sputtering at the power of 100 and 30 W, respectively, while SiO₂ was prepared in the radio frequency (RF) mode with power at 150 W. The background pressure of the chamber was pumped to lower than 4.5×10^{-6} Torr and argon with flow rate at 10 standard cubic centimeter per minute (SCCM) was injected into the chamber. The growth pressure was controlled at 1×10^{-3} Torr by a throttle valve.

The deposition rate for SiO₂ and ultrathin Cr film was calibrated by a variable-angle spectroscopic ellipsometer (ELLIP-SR-II, Shanghai Bright Enterprise Development Co., Shanghai, China). The ellipsometric parameters (Ψ , Δ) were obtained in the wavelength range of 300–1100 nm over three incident angles of 65°, 70°, and 75°. For the Cu and optically thick Cr film, a step profiler (Bruker, DektakXT stylus profiler, Karlsruhe, Germany) was adopted to obtain its film thickness. To obtain the optical constants of ultrathin Cr film in the long-wavelength range, a variable-angle spectroscopic ellipsometer with the measured wavelength range in 2.0–25.0 µm and incident angles at 65° and 75° was employed (IR-Vase II, J. A. Woollam, Lincoln, NE, USA).

The reflectance (*R*) and transmittance (*T*) spectra of the fabricated solar selective absorber were measured by a UV–Vis–NIR spectrophotometer (UV 3600 plus, Shimadzu) over the wavelength range from 250 to 2500 nm, which was calibrated by a standard Al reference sample. The incident angle was about 5 degrees. The absorptance (*A*) of the sample can be deduced by $A \approx 1 - R$, due to the negligible light transmittance from the thick metal reflection layer. The cross-section structure of the sample was characterized by a transmission electron microscope (TEM, Tecnai G2 F20, FEI, Hillsboro, OR, USA). The surface morphologies of the samples were characterized by atomic force microscopy (FSM-Nanoview 1000 AFM, Tapping mode, Fishman Suzhou, Suzhou, China) with the measured area of $10 \times 10 \ \mu\text{m}^2$.

4. Results and Discussion

In the ellipsometry analysis process, the Drude and Lorentz model (DL) and three oscillators were chosen to characterize the optical dispersion relation of Cr film [40]. A four-phase optical structural model consisting of air/roughness layer/Cr layer/Si substrate was used. The ellipsometric parameters in the wavelength range of 300–1100 nm and 2.0–25.0 µm were combined together and fitted at the same time. The Bruggeman effective medium approximation model was adopted to depict the roughness layer which is consisted of the Cr and void [41]. To reduce the fitting parameters, the void fraction was set to 50%, and the thickness of the roughness layer was set to be the same as the root mean square (RMS) value of the sample, as revealed by the AFM results (Supplementary Materials, Figure S1). In the fitting process, the film thickness for the bulk Cr layer was fixed at 165 nm as measured by the step profiler, while for the ultrathin Cr film, its film thickness was treated as the fitting parameter.

The measured and fitted ellipsometric parameters were presented in Figure 2. As can be seen, the fitting shows a good agreement with the experimental data in the entire measured spectral range over the different incident angles, indicating the accuracy and reliability of our fitting in the whole investigated spectrum range. The film thickness of the ultrathin Cr film was also obtained to be 12.3 nm.



Figure 2. Measured (symbol) and fitted (line) ellipsometric parameters for (**a**,**b**) bulk Cr film, and (**c**,**d**) ultrathin Cr film.

The optical constants of refractive index n and extinction coefficient k of the bulk and ultrathin Cr film in accompany with the reference were depicted in Figure 3 [30]. The data in the wavelength range of 1100–2000 nm were extrapolated from the fitted DL model parameters. The extinction coefficients for the bulk Cr film increase with the wavelength, showing a metal optical dispersion behavior. The difference between the optical constants of our Cr sample and the reference, particularly in the long-wavelength range, which may be due to the different fabrication methods and deposition conditions like, sputtering power, substrate temperature, argon pressure and so on for the Cr sample [42,43]. Optical constants of the deposited bulk and ultrathin Cr film also show a difference. It should be due to the thickness-dependent effect of the optical constants for thin metal film, especially for film with thickness smaller than its electron mean free path [33]. The differences between bulk and the ultrathin metal film will inevitably lead to a huge error in the design of solar selective absorber and other related optoelectronic devices.



Figure 3. Optical constants (**a**) refractive index *n*, and (**b**) extinction coefficient *k* of the fabricated Cr samples, in comparison with the reference [30].

The optical constants of ultrathin Cr film with film thickness of 12.3 nm in the wavelength range of 250–25,000 nm were introduced into the optimization process in the design of the six-layered solar selective absorber. The targeted working condition was: a temperature of 600 K and a solar concentration of 1 Sun. The optimized film structure was: Cr (3.7 nm)/SiO₂ (61.9 nm)/Cr (24.8 nm)/SiO₂ (7.2 nm)/Cu (>100.0 nm). Numerical results indicate that the film thickness of the top SiO₂ is zero. However, in practical applications, the top dielectric layer also serves as the protective layer.

Hence, we added 10-nm SiO_2 on the top of the designed film structure in the fabrication of ultrathin Cr film-based solar selective absorber, which will have negligible influences on its reflectance spectra of the multilayered film structure. At the working condition of 600 K and 1 Sun, the designed solar selective absorber has a photothermal conversion efficiency of 63.4%.

Figure 4a shows the reflectance spectra of the fabricated sample and the numerical simulations by using the optical constants of Cr from 12.3-nm Cr film, bulk Cr film, or literature data, respectively in the wavelength range of 250–2500 nm [30]. Due to limited experimental tools in our Lab, the reflectance spectra in the wavelength range of 2500–25,000 nm was not measured. As can be clearly seen, the simulated results with the optical constants of ultrathin Cr film show a good agreement with the measurements, proving the significance of using the optical constants of the ultrathin metal film. In comparison, both of the reflectance spectra by employing the optical constants of bulk Cr film and literature data have a large discrepancy with the measured results, demonstrating the significance of using the optical constants of bulk Cr film and literature data have a large from 300 to 1200 nm and increases rapidly in the long-wavelength range, implying its high solar absorptance and good spectral selectivity. The cross-sectional image of the fabricated sample revealed by the TEM is presented in Figure 4b. The film thickness of each layer can be obtained to about: SiO₂ (10.2)/Cr (2.9 nm)/SiO₂ (60.9 nm)/Cr (23.2 nm)/SiO₂ (7.2 nm)/Cu (>100.0 nm), which is consistent with the design in consideration of the measurement errors.



Figure 4. (**a**) Reflectance spectra of the deposited sample and design, (**b**) cross-sectional image of the fabricated sample.

To verify the effects of different optical constants between the ultrathin Cr film and literature data on the design of multilayer solar selective absorber, we designed the six-layered solar selective absorbers aiming to operate at the temperature of 600 K by using the optical constants of Cr film from the measurements or literature data, respectively. The optimized film structure for each solar selective absorber was listed in Table S1 (Supplementary Materials). Figure 5a shows the obtained reflectance spectra for the nano-Cr based and literature-data based solar selective absorber at the solar concentration of 1 Sun and 100 Sun, respectively. As can be seen, the difference in the optical constants between the measured nano-Cr film and literature data can produce a large difference in the reflectance spectra of the optimized solar selective absorber. The solar photothermal conversion efficiency (PTCE), solar absorptance, and thermal emittance of the designed solar selective absorber based on the measured optical constants or the literature data for the Cr film were presented in Figure 5b. As shown, at the solar concentration of 1 Sun, the PTCE and solar absorptance of the designed solar selective absorbers based on the measured optical constants or the literature data for the Cr film were presented in Figure 5b. As shown, at the solar concentration of 1 Sun, the PTCE and solar absorptance of the designed solar selective absorbers based on the measured optical constants or the literature data show a large discrepancy, while they have the nearly the same value for the solar concentration of 100 Sun.



Figure 5. (a) Reflectance spectra of the designed six-layer solar selective absorber with Cr layer's optical constants obtained from the measured ultrathin nano-Cr layer or literature data for bulk Cr layer; (b) the solar photothermal conversion efficiency (PTCE), solar absorptance, and thermal emittance of the designed solar selective absorber based on the measured optical constants or the literature data for Cr film.

Based on the measured optical constants for the ultrathin Cr film, we also numerically designed and optimized various nano-Cr film based six-layer metal/dielectric solar selective absorbers targeted at different operating temperatures and solar concentrations. The obtained results were listed in Table S2 (Supplementary Materials). At 1 Sun, the reflectance spectra for the operating temperature of 300, 400, 500, 600, and 700 K are depicted in Figure 6a. As can be seen, with the increase of temperature, the low-reflectance spectra range gradually decreases and shifts to the short wavelength region. As temperature rising, the Planck's blackbody radiation spectrum will move to the shorter wavelength region and overlap more with the solar radiation spectrum, resulting in an increase of the thermal emittance. Moreover, in the second term of the expressions for PTCE: $\eta_t = B\alpha - \frac{\varepsilon \sigma T}{c}$ it is the product of thermal emittance and the fourth power of temperature. To obtain the highest PTCE, the low-reflectance spectra region should move to the shorter wavelength region. The obtained reflectance spectra for the solar selective absorber working at the solar concentration of 1, 5, 10, 50, and 100 Suns with temperature fixed at 600 K are presented in Figure 6b. With the increase of solar concentrations, the second term of the expressions for PTCE will decrease and can be ignored for large solar concentrations. Hence, the influence of thermal radiation gets smaller and smaller. The absorption spectrum will extend to the long-wavelength range.

Figure 6c shows the influences of operating temperature on the solar absorptance, thermal emittance, and solar PTCE of the designed six-layer metal/dielectric solar selective absorber. As described, nearly all of the solar absorptances, thermal emittances and solar PTCEs decrease with the rising of temperature. It is mainly because of the fourth power temperature relation in the second term of the expression of solar PTCE. As a comparison, the effects of solar optical concentrations on the performance of solar selective absorber were also investigated with the results shown in Figure 6d. At the 1-Sun concentration condition, the solar PTCE is about 63%, while it increases to about 95% and is close to the value of solar absorptance at 100 Suns. This demonstrates the significance of solar concentration on the performance of solar PTCEs increase with the increase of solar concentrations. With the increase of solar concentration, the influences of solar concentration on the thermal emittance become weaker and can be ignored when solar concentration is higher than 50 Suns. Under the higher solar concentration condition, the solar selective absorber can be designed by just optimizing solar absorptance of the multilayered film structure.



Figure 6. Reflectance spectra of the six-layer solar selective absorbers: (**a**) working temperature at 300, 400, 500, 600, and 700 K with solar concentration at 1 Sun; (**b**) working at 1, 5, 10, 50, and 100 Suns with the temperature at 600 K; influences of (**c**) temperatures (1 Sun), and (**d**) solar concentrations (600 K) on the performances of the six-layer solar selective absorbers.

5. Conclusions

In this work, a program based on the transfer matrix method and the genetic algorithm was adopted to design solar selective absorber working at a specific temperature and solar concentration. More importantly, optical constants of ultrathin metal film, rather than the bulk film, were employed in the optimization process, which is of significance in consideration of the thickness-dependent optical constants of thin metal films, especially for film with thickness smaller than its electron mean free path. The measured reflectance spectra of the fabricated ultrathin Cr film-based solar selective absorber shows a good agreement with the simulated results, demonstrating the usefulness of the proposed program in the practical design of solar selective absorber and the significance to consider the actual optical constants of the semi-transparent metal absorption layer. The influences of working temperatures and solar concentrations on the performance of solar selective absorber were carefully investigated. Results show that all of the solar absorptances, thermal emittances and solar PTCEs decrease with the increase of solar concentrations while solar concentration exhibits a contrary trend. The impact of solar concentration can be ignored when it is higher than 50 Suns. The results will be very helpful to guide the experiments in the design of multilayered solar selective absorber for high efficient solar-thermal conversion.

Supplementary Materials: The following are available online at http://www.mdpi.com/2079-6412/10/10/938/s1, Figure S1: AFM images of the fabricated (a) bulk, and (b) 12.3-nm Cr film, Table S1: Optimized film structure for the six-layered solar selective absorber by using the optical constants of Cr film from the measurements or literature data [30], Table S2: Optimized film thickness for each layer of six-layer solar selective absorber aiming to work at different temperatures and solar concentrations based on the measured optical constants of the ultrathin Cr layer.

Author Contributions: Conceptualization, E.-T.H. and K.-H.Y.; methodology, Z.-Y.W., Q.-Y.C. and H.-T.T.; software, Z.-Y.W. and E.-T.H.; formal analysis, Z.-Y.W. and J.W.; investigation, Z.-Y.W. and E.-T.H.; writing—original draft preparation, Z.-Y.W. and E.-T.H.; writing—review and editing, L.-Y.C., W.W., K.-H.Y. and E.-T.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by [National Natural Science Foundation of China, Grant Nos. 61605089, 61427815, and 61805267], [NUPTSF, Grant No. NY218107], [the STCSM project of China, Grant No. 18ZR1445400], [Research Center of Optical Communications Engineering & Technology, Jiangsu Province, Grant No. ZXF201903], [the Youth Innovation Promotion Association CAS, Grant No. 2019241].

Conflicts of Interest: The authors declare no conflict of interest.

References

- Wang, X.; Gao, J.; Hu, H.; Zhang, H.; Liang, L.; Javaid, K.; Zhuge, F.; Cao, H.; Wang, L. High-temperature tolerance in WTi-Al₂O₃ cermet-based solar selective absorbing coatings with low thermal emissivity. *Nano Energy* 2017, *37*, 232–241. [CrossRef]
- Hu, E.-T.; Guo, S.; Gu, T.; Zang, K.-Y.; Tu, H.-T.; Cai, Q.-Y.; Yu, K.; Wei, W.; Zheng, Y.-X.; Wang, S.-Y.; et al. High efficient and wide-angle solar absorption with a multilayered metal-dielectric film structure. *Vacuum* 2017, 146, 194–199. [CrossRef]
- 3. Bermel, P.; Lee, J.; Joannopoulos, J.D.; Celanovic, I.M.S. Selective Solar Absorbers. In *Annual Review of Heat Transfer*; Chen, G., Prasad, V., Jaluria, Y., Karni, J., Eds.; Begell House, Inc.: New York, NY, USA, 2012; pp. 231–254.
- 4. Zhou, L.; Tan, Y.; Wang, J.; Xu, W.; Yuan, Y.; Cai, W.; Zhu, S.; Zhu, J. 3D self-assembly of aluminium nanoparticles for plasmon-enhanced solar desalination. *Nat. Photonics* **2016**, *10*, 393. [CrossRef]
- 5. Wang, H.; AlShehri, H.; Su, H.; Wang, L. Design, fabrication and optical characterizations of large-area lithography-free ultrathin multilayer selective solar coatings with excellent thermal stability in air. *Sol. Energy Mater. Sol. Cells* **2018**, *174*, 445–452. [CrossRef]
- Dyachenko, P.N.; Molesky, S.; Petrov, A.; Störmer, M.; Krekeler, T.; Lang, S.; Ritter, M.; Jacob, Z.; Eich, M. Controlling thermal emission with refractory epsilon-near-zero metamaterials via topological transitions. *Nat. Commun.* 2016, *7*, 11809. [CrossRef] [PubMed]
- 7. Kennedy, C.E. *Review of Mid-to High-Temperature Solar Selective Absorber Materials*; NREL/TP-520-31267; National Renewable Energy Laboratory: Golden, CO, USA, 2002.
- Ning, Y.; Wang, W.; Wang, L.; Sun, Y.; Song, P.; Man, H.; Zhang, Y.; Dai, B.; Zhang, J.; Wang, C.; et al. Optical simulation and preparation of novel Mo/ZrSiN/ZrSiON/SiO₂ solar selective absorbing coating. *Sol. Energy Mater. Sol. Cells* 2017, 167, 178–183. [CrossRef]
- 9. Sakurai, A.; Tanikawa, H.; Yamada, M. Computational design for a wide-angle cermet-based solar selective absorber for high temperature applications. *J. Quant. Spectrosc. Racdiat. Transf.* **2014**, *132*, 80–89. [CrossRef]
- Chester, D.; Bermel, P.; Joannopoulos, J.D.; Soljacic, M.; Celanovic, I. Design and global optimization of high-efficiency solar thermal systems with tungsten cermets. *Opt. Express* 2011, 19 (Suppl. 3), A245. [CrossRef]
- 11. Li, X.-F.; Chen, Y.-R.; Miao, J.; Zhou, P.; Zheng, Y.-X.; Chen, L.; Lee, Y.-P. High solar absorption of a multilayered thin film structure. *Opt. Express* **2007**, *15*, 1907–1912. [CrossRef]
- 12. Zhou, W.-X.; Shen, Y.; Hu, E.-T.; Zhao, Y.; Sheng, M.-Y.; Zheng, Y.-X.; Wang, S.-Y.; Lee, Y.-P.; Wang, C.-Z.; Lynch, D.W.; et al. Nano-Cr-film-based solar selective absorber with high photo-thermal conversion efficiency and good thermal stability. *Opt. Express* **2012**, *20*, 28953–28962. [CrossRef]
- Chen, H.-P.; Lee, C.-T.; Liao, W.B.; Chang, Y.-C.; Chen, Y.-S.; Li, M.-C.; Lee, C.-C.; Kuo, C.-C. Analysis of High-Efficiency Mo-Based Solar Selective Absorber by Admittance Locus Method. *Coatings* 2019, *9*, 256. [CrossRef]
- 14. Wu, Y.; Zheng, W.; Lin, L.; Qu, Y.; Lai, F. Colored solar selective absorbing coatings with metal Ti and dielectric AlN multilayer structure. *Sol. Energy Mater. Sol. Cells* **2013**, *115*, 145–150. [CrossRef]
- 15. Meng, J.-P.; Liu, X.-P.; Fu, Z.-Q.; Zhang, K. Optical design of Cu/Zr_{0.2}AlN_{0.8}/ZrN/AlN/ZrN/AlN/Al₃₄O₆₂N₄ solar selective absorbing coatings. *Sol. Energy* **2017**, *146*, 430–435. [CrossRef]
- 16. Rodriguez-Palomo, A.; Céspedes, E.; Hernández-Pinilla, D.; Prieto, C. High-temperature air-stable solar selective coating based on MoSi₂–Si₃N₄ composite. *Sol. Energy Mater. Sol. Cells* **2018**, *174*, 50–55. [CrossRef]
- 17. Thomas, N.H.; Chen, Z.; Fan, S.; Minnich, A.J. Semiconductor-based Multilayer Selective Solar Absorber for Unconcentrated Solar Thermal Energy Conversion. *Sci. Rep.* **2017**, *7*, 5362. [CrossRef]
- 18. Chen, W.; Liu, J.; Ma, W.-Z.; Yu, G.-X.; Chen, J.-Q.; Cai, H.-Y.; Yang, C.-F. Numerical Study of Multilayer Planar Film Structures for Ideal Absorption in the Entire Solar Spectrum. *Appl. Sci.* **2020**, *10*, 3276. [CrossRef]

- 19. Blandre, E.; Shimizu, M.; Kohiyama, A.; Yugami, H.; Chapuis, P.-O.; Vaillon, R. Spectrally shaping high-temperature radiators for thermophotovoltaics using Mo-HfO2 trilayer-on-substrate structures. *Opt. Express* **2018**, *26*, 4346. [CrossRef]
- Shimizu, M.; Kohiyama, A.; Yugami, H. Evaluation of thermal stability in spectrally selective few-layer metallo-dielectric structures for solar thermophotovoltaics. *J. Quant. Spectrosc. Radiat. Transf.* 2018, 212, 45–49. [CrossRef]
- Hu, E.-T.; Liu, X.-X.; Yao, Y.; Zang, K.-Y.; Tu, Z.-J.; Jiang, A.-Q.; Yu, K.; Zheng, J.; Wei, W.; Zheng, Y.-X.; et al. Multilayered metal-dielectric film structure for highly efficient solar selective absorption. *Mater. Res. Express* 2018, 5, 066428. [CrossRef]
- 22. Sergeant, N.P.; Pincon, O.; Agrawal, M.; Peumans, P. Design of wide-angle solar-selective absorbers using aperiodic metal-dielectric stacks. *Opt. Express* **2009**, *17*, 22800–22812. [CrossRef]
- 23. El-Mahallawy, N.A.; Atia, M.R.; Khaled, A.; Shoeib, M. Design and simulation of different multilayer solar selective coatings for solar thermal applications. *Mater. Res. Express* **2018**, *5*, 046402. [CrossRef]
- 24. Du, M.; Hao, L.; Mi, J.; Lv, F.; Liu, X.; Jiang, L.; Wang, S. Optimization design of Ti_{0.5}Al_{0.5}N/Ti_{0.25}Al_{0.75}N/AlN coating used for solar selective applications. *Sol. Energy Mater. Sol. Cells* **2011**, *95*, 1193–1196. [CrossRef]
- Wu, Y.; Wang, C.; Sun, Y.; Xue, Y.; Ning, Y.; Wang, W.; Zhao, S.; Tomasella, E.; Bousquet, A. Optical simulation and experimental optimization of Al/NbMoN/NbMoON/SiO₂ solar selective absorbing coatings. *Sol. Energy Mater. Sol. Cells* 2015, 134, 373–380. [CrossRef]
- Gremion, C.; Seassal, C.; Drouard, E.; Gerthoffer, A.; Pelissier, N.; Ducros, C. Design, properties and degradation mechanisms of Pt-Al₂O₃ multilayer coating for high temperature solar thermal applications. *Surf. Coat. Technol.* 2015, 284, 31–37. [CrossRef]
- Kraemer, D.; Jie, Q.; McEnaney, K.; Cao, F.; Liu, W.-S.; Weinstein, L.A.; Loomis, J.; Ren, Z.; Chen, G. Concentrating solar thermoelectric generators with a peak efficiency of 7.4%. *Nat. Energy* 2016, *1*, 16153. [CrossRef]
- Jung, Y.S.; Jeong, D.H.; Kang, S.B.; Kim, F.; Jeong, M.H.; Lee, K.-S.; Son, J.S.; Baik, J.M.; Kim, J.; Choi, K.J. Wearable solar thermoelectric generator driven by unprecedentedly high temperature difference. *Nano Energy* 2017, 40, 663–672. [CrossRef]
- 29. Zhu, W.; Deng, Y.; Cao, L. Light-concentrated solar generator and sensor based on flexible thin-film thermoelectric device. *Nano Energy* **2017**, *34*, 463–471. [CrossRef]
- 30. Palik, E.D. Handbook of Optical Constants of Solids; Academic Press: New York, NY, USA, 1998.
- Liu, M.-H.; Hu, E.-T.; Yao, Y.; Zang, K.-Y.; He, N.; Li, J.; Zheng, Y.-X.; Wang, S.-Y.; Yoshie, O.; Lee, Y.; et al. High efficiency of photon-to-heat conversion with a 6-layered metal/dielectric film structure in the 250–1200 nm wavelength region. *Opt. Express* 2014, 22, A1843–A1852. [CrossRef]
- 32. Hu, E.-T.; Zhang, R.-J.; Cai, Q.-Y.; Wang, Z.-Y.; Xu, J.-P.; Zheng, Y.-X.; Wang, S.-Y.; Wei, Y.-F.; Huang, R.-Z.; Chen, L. Study of the thickness effect on the dielectric functions by utilizing a wedge-shaped Ti film sample with continuously varied thickness. *Appl. Phys. A* **2015**, *120*, 875. [CrossRef]
- Gao, X.-H.; Guo, Z.-M.; Geng, Q.-F.; Ma, P.-J.; Liu, G. Structure, optical properties and thermal stability of TiC-based tandem spectrally selective solar absorber coating. *Sol. Energy Mater. Sol. Cells* 2016, 157, 543–549. [CrossRef]
- Zhang, K.; Hao, L.; Du, M.; Mi, J.; Wang, J.-N.; Meng, J.-P. A review on thermal stability and high temperature induced ageing mechanisms of solar absorber coatings. *Renew. Sustain. Energ. Rev.* 2017, 67, 1282–1299. [CrossRef]
- 35. Macleod, H.A. Thin-Film Optical Filters, 4th ed.; CRC Press: Boca Raton, FL, USA, 2010.
- 36. Skowroński, Ł.; Szczesny, R.; Zdunek, K. Optical and microstructural characterization of amorphous-like Al₂O₃, SnO₂ and TiO₂ thin layers deposited using a pulse gas injection magnetron sputtering technique. *Thin Solid Film* **2017**, *632*, 112–118. [CrossRef]
- Hu, E.-T.; Guo, S.; Gu, T.; Zang, K.-Y.; Yao, Y.; Wang, Z.-Y.; Yu, K.; Wei, W.; Zheng, Y.-X.; Wang, S.-Y.; et al. Enhancement of solar absorption by a surface-roughened metal-dielectric film structure. *Jpn. J. Appl. Phys.* 2017, 56, 112301. [CrossRef]
- Cai, Q.-Y.; Zheng, Y.-X.; Mao, P.-H.; Zhang, R.-J.; Zhang, D.-X.; Liu, M.-H.; Chen, L.-Y. Evolution of optical constants of silicon dioxide on silicon from ultrathin films to thick films. *J. Phys. D Appl. Phys.* 2010, 43, 445302. [CrossRef]

- 39. Chipperfield, J.A.; Fleming, P.J. The MATLAB genetic algorithm toolbox. In Proceedings of the IEE Colloquium on Applied Control Techniques Using MATLAB 1995, London, UK, 26 January 1995; pp. 10/1–10/4.
- 40. Rakić, A.D.; Djurišić, A.B.; Elazar, J.M.; Majewski, M.L. Optical properties of metallic films for vertical-cavity optoelectronic devices. *Appl. Opt.* **1998**, *37*, 5271. [CrossRef] [PubMed]
- 41. Aspnes, D.E. Optical properties of thin films. Thin Solid Film 1982, 89, 249. [CrossRef]
- 42. Tompkins, H.G.; Baker, H.J.; Convey, D. Effect of process parameters on the optical constants of thin metal films. *Surf. Interface Anal.* **2015**, *29*, 227–231. [CrossRef]
- 43. Savaloni, H.; Khakpour, A.R. Substrate temperature dependence on the optical properties of Cu and Ag thin films. *Eur. Phys. J. Appl. Phys.* **2005**, *31*, 101–112. [CrossRef]



© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).