Solar Energy Materials and Solar Cells 169 (2017) 270–279

Contents lists available at ScienceDirect

Solar Energy Materials and Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Absorption mechanism and performance characterization of CuO nanostructured absorbers

Dasol Jeong[a], Junghun Lee[a], Hiki Hong[a], Dukhyun Choi[a], Jin-Woo Cho[b], Sun-Kyung Kim[b,*], Youngsuk Nam[a,*]

[a] Kyung Hee University, Department of Mechanical Engineering, Yongin, South Korea
[b] Kyung Hee University, Department of Applied Physics, Yongin, South Korea

ARTICLE INFO

Keywords:
Solar
Absorber
CuO
TiNOX
Double glazing
Collector

ABSTRACT

We introduce copper oxide (CuO) nanostructured selective solar absorbers having a broadband solar absorption over visible to near infrared wavelengths while suppressing long wavelength emission. The detailed mechanism enabling the enhanced solar absorption was investigated using the finite-difference-time-domain (FDTD) simulations. Both indoor and outdoor solar absorption experiments were conducted to investigate the performance of the suggested absorber in a well-controlled and actual operating conditions, respectively. The combined effects of the suggested absorber and double-glazing layout were also investigated. The results show that the sharp morphology of the CuO structures and its random size distribution enable the enhanced broadband optical absorption, and the resulting performance was measured to be approximately 95% and 97% of that of the current state-of-the-art TiNOX absorber for single and double glazing case, respectively. The suggested absorbers can provide a near-equivalent performance with the current-state-of-the-art solar absorber with much simpler and faster fabrication process. Furthermore, the numerical and experimental frameworks provided in this study will help develop high efficiency solar collectors.

1. Introduction

Solar thermal energy is one of the most abundant renewable energy sources applicable to various energy systems including buildings and power plants. In such systems, solar irradiation is converted to thermal energy through solar collectors. Within such collectors, an absorber surface is a core component since its radiative properties significantly affect solar absorption capacity, re-emission heat loss and resulting solar to thermal conversion efficiency. Therefore, it is crucial to obtain a spectrally-selective absorber surface with a high absorptivity in UV–visible and near-infrared regions as well as a low emissivity in a long wavelength region.

To develop such selective absorbers, many researchers have exploited various strategies utilizing light interference, scattering, resonance and tandem effects [1]. Interference of light can be tailored by incorporating the wavelength-scale multi coating layers. Previous studies have introduced multilayer absorbers such as Cr/CrTiAlN-G/TiAlN/AlSiN/AlSiO [2] or Mo/TiAlN/TiAlON/Si_3N_4 [3] using the physical vapor deposition technique. These fabrication methods can precisely control the coating thickness and obtain a desirable spectral selectivity ($\alpha > 0.95$, $\varepsilon < 0.1$), however, such absorbers require vacuum-based equipment, which limits applying such techniques to surfaces with a large area or complex geometries.

Tailoring light scattering and resonance were also demonstrated using a wavelength-scale nanostructuring. Previous studies demonstrated the surface-textured absorbers fabricated by the photolithography techniques, and obtained a desired morphology and high spectral selectivity ($\alpha > 0.9$, $\varepsilon < 0.2$) [4,5]. Periodic nano-pyramid nickel absorber with anti-reflection coating was proposed using the interference lithography technique. This nanoscale pyramid structure can gradually change effective refractive index and improve solar absorption by matching wave impedance. This pyramidal nickel absorber showed excellent thermal stability (up to 800 °C for 8 h) and selectivity ($\alpha > 0.95$, $\varepsilon < 0.1$) [4]. Trapezoidal tantalum array on MgF_2 dielectric layer was also introduced for solar absorbers using the electron beam lithography. This periodic structure on dielectric film can enhance solar absorption by occurring surface plasmon and magnetic polariton. This absorber showed good spectral selectivity (α~0.9, ε~0.2) and thermal stability (up to 350 °C) [5], however, the limited scalability and the equipment cost may limit the practicality of such absorbers.

Tandem effects can be achieved by incorporating two different materials including absorber and reflector layers. Previous studies have

* Corresponding authors.
E-mail addresses: sunkim@khu.ac.kr (S.-K. Kim), ysnam1@khu.ac.kr (Y. Nam).

http://dx.doi.org/10.1016/j.solmat.2017.05.029
Received 27 January 2017; Received in revised form 7 May 2017; Accepted 14 May 2017

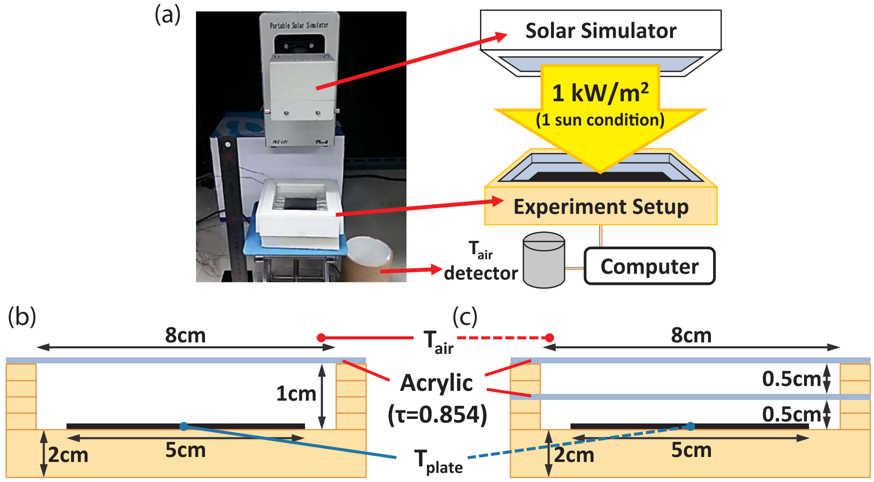

Fig. 1. (a) Photo and schematic of the entire indoor test setup including the solar simulator (PEC-L01, Peccell), (b-c) Schematic of the tested sample with single glazing (SG) (b) and double glazing (DG) layout (c). The setup includes a solar absorber sample (5 cm × 5 cm) and the total air gap was set to be 1 cm in total. For the indoor test, acrylic plate ($\tau = 0.854$) was applied.

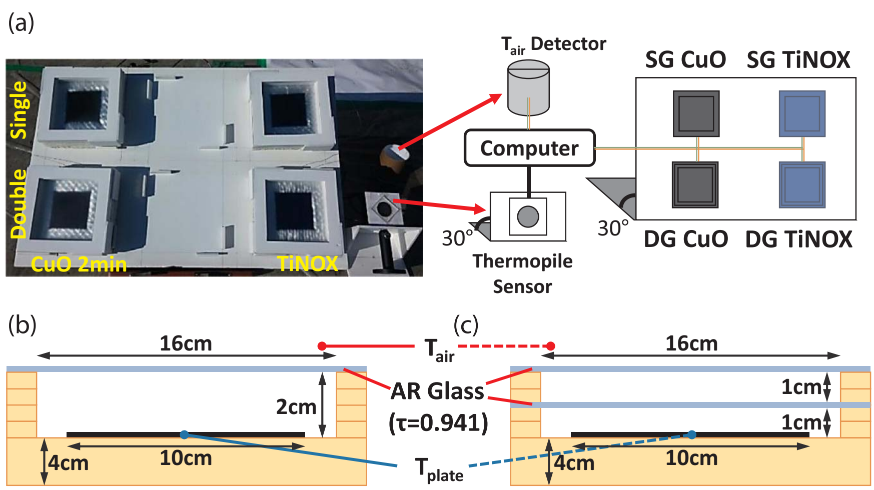

Fig. 2. (a) Photo and schematic of the entire outdoor test setup including four different absorber surfaces, (b-c) Schematic of the tested sample with single glazing (SG) (b) and double glazing (DG) layout (c). The setup includes a solar absorber sample (10 cm × 10 cm) and the total air gap was set to be 2 cm. For the outdoor test, anti-reflection (AR) coated glass ($\tau = 0.941$) was applied.

reported various solar absorbers incorporating metal oxides such as chrome oxides [6,7], cobalt oxides [8,9], and copper oxides [10–13] on top of metal substrates. In such absorbers, metal oxides absorb the short wavelength photons whose energy is larger than the bandgap of metal oxides, while underneath metal layers reflect the long wavelength photons. Chrome or cobalt oxides deposited on a nickel substrate by electrodeposition showed a good optical property ($\alpha > 0.9$, $\varepsilon < 0.2$) and thermal stability (up to 350 °C). Among various metal-oxides, copper oxides formed by a simple chemical oxidation process have attracted attentions for solar collectors due to their simple fabrication process and relatively high performance. Copper is a good infrared (IR) mirror and cupric oxide (CuO) is a p-type semiconductor with bandgap of 1.3–1.5 eV [14] that allows copper oxide absorbers effectively absorbs UV–visible to near IR irradiation while suppressing the re-emission loss through a long wavelength IR.

Previous studies have suggested various copper oxide based selective absorbers using wet chemical processes [10–13]. Pebble-like copper oxides fabricated using the solution including $NaClO_2$, NaOH and DI water heated at 65 °C was suggested but this absorber showed relatively poor solar absorptivity ($\alpha \sim 0.89$, $\varepsilon \sim 0.08$) due to the relatively short morphology of copper oxides [10]. Fiber-like copper oxides fabricated with 0.0025 M NaOH solution showed a high spectral selectivity ($\alpha \sim 0.94$, $\varepsilon \sim 0.08$) but the required process time was too long (96 h) due to the slow reaction rate of the NaOH solution. Porous copper oxide fabricated by the solution including NaClO, NaOH and DI water at 80 °C was also investigated. This absorber showed a desirable optical property ($\alpha \sim 0.94$, $\varepsilon \sim 0.08$) but its thermal stability was limited.

Despite these efforts, most of the previous metal-oxide absorber studies simply reported the spectral property of the surfaces measured at room temperature and the experimental characterization of surfaces at the actual operating condition is rare. More importantly, few studies have investigated the detailed physical mechanism inducing the desired absorption performance on the absorbers. In addition, the combined effects between the suggested absorbers and double-glazing layout have not been investigated. Since it is still challenging to completely eliminate the heat loss through long-wavelength emission from the absorbers, it may be beneficial to couple such absorbers with multi-glazing layout. Previous studies have suggested double-glazing solar collector with TiNOX absorber to increase the thermal insulation capacity and reported meaningful increase in the conversion efficiency compared with a single glazing one [15–18].

In this work, we suggested copper oxide (CuO) nanostructured solar absorbers fabricated by simple and scalable wet-chemical oxidation process. The hot alkaline solution composed of NaClO, NaOH, Na_3PO_4 and DI water was applied with optimizing the oxidation time considering the conflict between the solar absorption and re-emission loss. The