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Spectrally selective solar absorber stable up to 900°C for 120 hours under ambient conditions

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ABSTRACT

Concentrated solar power (CSP) technology, which converts sunlight into heat and then electricity, is an attractive alternative to photovoltaics because of its high capacity for thermal-energy storage, which can be converted, to electricity after sunset. As the efficiency of this technology is limited by the Carnot efficiency, higher absorber temperatures are desirable. At high temperatures conversion efficiency is limited by heat loss from solar absorbers via radiation in infrared wavelengths. Hence, it is desirable to develop selective solar absorbers, which can absorb solar radiation while reflecting infrared radiation. It is also important to develop high temperature selective solar absorbers, which can work in ambient conditions to reduce cost as compared to those that work under vacuum. Here, we report a selective solar absorber made of black chrome/ITO/SiO₂, deposited on stainless steel, which showed stable performance at 900°C under ambient conditions for 120 hours. The proposed selective solar absorber exhibits an absorptance of 0.9 in the solar spectrum with an infrared emittance of 0.4 beyond wavelengths of 6 µm.
1. Introduction

Concentrated solar power (CSP) industry is moving towards supercritical CO\textsubscript{2} cycles (Irwin and Le Moullec, 2017), which require heat input around 700°C to increase the efficiency. Therefore, it is critical to develop technologies to convert solar energy into high temperature thermal energy for a sustainable future. Solar radiation is converted to thermal energy using a solar absorber. Spectrally selective solar absorbers (SSA) absorb a high fraction of the incident solar radiation, while simultaneously suppressing thermal reradiation. This is achieved through a high absorptance, \(\alpha\) (low reflectance, \(R\)) in the solar spectrum and a low emittance, \(\varepsilon\) (high reflectance) in the infrared (IR) spectrum (Ho et al., 2014). Different designs have been proposed, including intrinsically selective materials (McDonald, 1975), semiconductor–metal stacks (Kats et al., 2013), metal–dielectric stacks (Wang and Wang, 2015; Wang et al., 2018), cermet coatings (Cheng et al., 2013), nanowire arrays (Wang et al., 2017), textured surfaces (Jain and Pitchumani, 2017) and metamaterials consisting of micro/nanostructures. Literature reviews by Selvakumar and Barshilia (2012) and Kennedy (2002) provide a comprehensive overview on the performance of these SSA. However, three problems still remain mostly unaddressed in literature:

1) It is important to develop high temperature selective solar absorbers which can work in ambient conditions to reduce cost as compared to those that work under vacuum. To best of our knowledge, none of the SSA designs so far has shown stable performance at higher temperatures (\(\geq 700^\circ\text{C}\)) under ambient conditions for more than 26 hours (see Table 1).
2) Stable performance of SSA at higher temperatures (≥700°C) for more than 30 hours was only reported under vacuum (Cao et al., 2017; Gao et al., 2016).

3) For the majority of high temperature SSA, either no thermal cycling was done or the cycling conditions used did not reflect a real diurnal cycle owing to shorter holding times.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Stability in ambient conditions (air)</th>
<th>Optical properties</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiAlN/TiAlSiN/Si3N4 on SS</td>
<td>272°C / 600°C</td>
<td>0.938</td>
<td>0.099</td>
</tr>
<tr>
<td>AlxOy–Al–AlxOy on Mo</td>
<td>300°C</td>
<td>0.936</td>
<td>0.05</td>
</tr>
<tr>
<td>TiAlN/CrAlON/Si3N4 on Cu</td>
<td>300°C / 550°C</td>
<td>0.927</td>
<td>0.1 (82°C)</td>
</tr>
<tr>
<td>Ti/Cr, AITiN and AlTiON,AITiO</td>
<td>350°C</td>
<td>0.93</td>
<td>0.16</td>
</tr>
<tr>
<td>TiAlN/AION on Cu and SS</td>
<td>400°C / 600°C</td>
<td>0.946 (Cu)</td>
<td>0.07 (Cu)</td>
</tr>
<tr>
<td>CrAlO-based coating</td>
<td>500°C</td>
<td>0.923</td>
<td>0.149</td>
</tr>
<tr>
<td>AlCrSiN/AlCrSiON/AlCrO</td>
<td>600°C</td>
<td>0.924</td>
<td>0.16</td>
</tr>
<tr>
<td>Cu/TiAlCrN/TiAlN/AISiN on SS</td>
<td>700°C</td>
<td>1h</td>
<td>0.88 (SS)</td>
</tr>
<tr>
<td>Cr-Al-O based coating</td>
<td>700°C</td>
<td>2h</td>
<td>0.924</td>
</tr>
<tr>
<td>Mn-Cu-Co-Ox-ZrO2/MgF2</td>
<td>700°C</td>
<td>2h</td>
<td>0.97</td>
</tr>
<tr>
<td>TaSi2 multilayer</td>
<td>700°C</td>
<td>20h</td>
<td>0.945</td>
</tr>
<tr>
<td>(1) electroplated Co3O4 on silver</td>
<td>(1) 900°C</td>
<td>(1) 12h</td>
<td>0.9</td>
</tr>
<tr>
<td>(2) Co3O4 on platinum</td>
<td>(2) 1100°C</td>
<td>(2) 26h</td>
<td></td>
</tr>
<tr>
<td><strong>Our work: Black Chrome/ITO/SiO2</strong></td>
<td>(1) 800°C</td>
<td>(1) 120h</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>(2) 800°C / 900°C</td>
<td>(2) 60h / 60h</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 provides performance overview of SSA designs tested under ambient conditions at either higher temperatures (≥700°C) or for longer times (≥100 hours) in mid-temperatures (≤700°C).

The state-of-the-art for SSA with high-temperature stability under ambient conditions is Pyromark 2500, which is a silicone-based paint and seems to be optically stable below 650°C.
(Ho et al., 2014). Nevertheless, its spectral selectivity is very poor with a solar absorptance of ~0.95 and an IR emittance more than 0.8. Transparent conductive oxides (TCO) such as indium tin oxide (ITO) and fluorine doped tin oxide (FTO) have demonstrated high-temperature stability and thus show potential for the design of high-temperature SSA (Gregory et. al, 2002). The stability of a previously fabricated ITO/Si absorber (Goldner and Haskal, 1975) was not tested, and although the stabilities of ITO/Ta (Shimizu et al., 2014) and ITO/W absorbers (Shimizu et al., 2017) were evaluated, the tests were conducted in vacuum for 3 hours at 500°C and 10 hours at 700°C, respectively. As these studies were performed under vacuum conditions, effect of oxidation on their radiative properties is not known.

In this paper, we report a selective solar absorber made up of black chrome/ITO/SiO$_2$ which showed stability up to 900°C for at least 120 hours under ambient conditions. The black chrome enabled a high absorption in the visible spectrum and ITO provided enhanced reflectance in the infrared (IR) region. To get the desired performance the structure and material were systematically optimized. Optical measurements revealed a solar absorptance of ~0.9 and an IR emittance of 0.4 ($R = 0.6$) beyond wavelengths of 6 µm. The thermal stability of the SSA structure was then investigated by subjecting it to multiple thermal cycling for longer holding times at higher temperatures, simulating the diurnal solar cycle. In addition, we carried out optical measurements of our sample at various temperatures to understand the temperature dependence of the IR reflectance.

2. Experimental Details

2.1 Sample Preparation

The solar absorber structure was fabricated using magnetron sputtering, with the ITO and SiO$_2$ layers sputtered on top of black chrome. Black chrome was purchased from Metal Surfaces Inc, where ~5µm thick layer of black-chrome was electroplated on stainless steel (SS-304). The
received black chrome samples were cut to a size of 25mm x 25mm. The ITO layer (90 wt% In$_2$O$_3$, 10 wt% SnO$_2$) was then RF-sputtered onto black chrome using a base pressure of 10$^{-6}$ Torr, sputtering power of 100 W, argon pressure of 5 mTorr, and partial oxygen pressure of 0%. The ITO layer was deposited with substrate heating at 300°C. The SiO$_2$ layer was deposited on top of ITO layer by RF sputtering using a base pressure of 10$^{-6}$ Torr, power of 150 W, and argon pressure of 3 mTorr. During the deposition, the substrate holders were rotating to ensure uniform thickness of the layers.

2.2 Optical and Structural Characterization

Two types of optical measurements were conducted:

1) At room temperature: The visible/near infrared (NIR) reflectance (0.25–2.5 µm) was measured at room temperature using a Lambda 950 UV/VIS spectrometer (Perkin Elmer Inc.) at an incidence angle of 8°. The IR reflectance (2.5–20 µm) for the absorber was measured using a FTIR spectrometer (Thermo Fisher Scientific) along with a gold-coated IR integrating sphere (Pike Technologies) at an incidence angle of 12°. An aluminum mirror was used as the reference for the reflectance measurement in the IR range, and Spectralon was used as the reference for the reflectance measurements in the visible and NIR range. The measured reflectance was calculated using $S_{\text{sample}} / S_{\text{ref}} \times R_{\text{ref}}$, where $S_{\text{sample}}$ and $S_{\text{ref}}$ are the reflected signal measured from the sample and the reference, respectively, and $R_{\text{ref}}$ is the reflectance of the corresponding reference.

2) At high temperatures imitating the operating conditions: To measure the reflectance at high temperature, the FTIR signal was coupled into one fiber leg of a Y-shape fiber bundle using a fiber coupler (Fibermate2, Harrick Scientific Products, Inc.). The signal was guided to the sample surface by the fiber, with the sample placed on a customized
heater and maintained at the target temperature. The heating rate was not constant for the high-temperature reflectance measurement as we controlled the heating power. The sample was maintained at target temperature for 30 minutes. The reflected signal was re-collected by the Y-shape fiber head and transmitted to the FTIR detector through the other fiber leg. An aluminum mirror was used as the reference for the reflectance measurement, and a sliding rail was used to switch the measurement between the reference mirror and sample. Two different Y-shape fiber bundles were used for the different wavelength ranges (visible/NIR fiber: Thorlabs, RP21; IR fiber: High Tech Photonics, AP10757). The ITO absorber temperature was assumed to be same as the temperature of the copper plate (<1cm in thickness) under it due to the small thermal resistance. We also measured the emission from the sample at high temperature by turning off the FTIR source and it accounted for <1%. Also, the emission collected from the sample won’t affect the measurement since this emission signal is not modulated by the FTIR and will not be amplified. The experimental setup is based on a previous high temperature setup used by one of the co-authors (Wang et al., 2015).

For the thermal aging studies, the samples were heated up in a muffle furnace (Thermolyne FB1315M). The air temperature inside the furnace was assumed to be same as the absorber temperature because of the low thermal mass of the sample. A ramp-up rate of 20°C/min was used and two different holding times (5h/10h) were investigated. The samples were furnace cooled after their holding time.

Composition characterization of the pristine and thermally cycled samples was carried out using Rutherford Back Scattering (RBS). Zeiss Gemini Ultra-55 Field Emission Scanning
Electron Microscope Scanning Electron Microscopy (SEM) was used for imaging of the samples before and thermal treatment.

3. Results and Discussion

3.1 Design of SSA and Theoretical Modeling

A schematic of the proposed SSA that consists of a four-layer multilayer stack of SiO$_2$, ITO, and black chrome on a stainless-steel (SS 304) substrate is shown in Figure 1. Instead of using conventionally applied metals (such as Ta and W) as the absorbing layer, we explored the usage of black-chrome coated stainless steel. Optically opaque black-chrome-coated (~5 µm) stainless steel 304 (Metal Surfaces Inc.) is highly absorptive from the visible spectral range up to 10 µm. The ITO layer on top of the black chrome is transparent in the visible and near-infrared (NIR) range because of its high bandgap of ~4 eV but is electrically conductive and therefore optically reflective in the IR range because of its strong tin doping (Hamberg and Granqvist, 1985). Therefore, the ITO selectively transmits the visible and NIR radiation to the black chrome layer, which is then absorbed, but reflects IR radiation. For an opaque optical structure, strong IR reflection indicates weak IR absorption/emission because $\varepsilon_\lambda = 1 - R_\lambda$. Therefore, the proposed structure is expected to exhibit strong visible and NIR absorption but weak IR absorption/emission. Finally, the SiO$_2$ layer on top serves as an anti-reflection coating that further reduces the visible/NIR reflection.
Figure 1: Schematic of proposed high-temperature selective solar absorber structure. ITO is transparent in visible and semi-transparent in the near IR spectrum. ITO is reflecting in IR. This allows the solar radiation to get absorbed while high reflectivity in IR results in low emissivity.

The multilayer structure was designed by optimizing the optical properties using the transfer matrix method (Zhang, 2007). The performance of the absorber was optimized to maximize the short wavelength absorptance and minimize long wavelength emittance. The optical constants for SiO$_2$ were obtained from literature (Palik, 1998), those for black chrome were calculated from its measured reflectance, based on the Kramers-Kronig relations. The Drude model (Chen et al., 2010) was used to determine the optical constants of ITO using a carrier concentration and relaxation time of $3.8 \times 10^{20}$ cm$^{-3}$ and 6.6 fs, respectively (Chen et al., 2010). Through a systematic study of both electrical and radiative properties Chen et al. (2010) have shown that carrier concentration is a strong function of film thickness where as the relaxation time was relatively constant. Since our ITO thickness is 500 nm, we chose the carrier concentration and relaxation time corresponding to ITO film thickness close to 500 nm from Chen et al.

Figure 2a presents the hemispherical reflectance values at near-normal incidence for the as-fabricated sample and the sample annealed at 800°C for 3h under ambient conditions. After annealing, the visible absorptance ($\alpha=\varepsilon=1-R$) decreased from ~0.95 to ~0.9 while the IR emittance increased from 0.2 to ~0.4. Using the Drude model, we re-fitted the free carrier concentration of ITO for our sample. A carrier concentration of $5.9 \times 10^{20}$ cm$^{-3}$ was obtained for the sample before annealing. This carrier concentration is ~ 50% higher than that assumed in the
design of the multilayer structure. The relaxation time was still assumed to be 6.6 fs as Chen et al. (2010) showed that it does not change much. In future studies we plan to validate this assumption for our films.

The difference between this value and that initially used to design the structure stems from the difference in the ITO target and actual ITO deposition parameters. For the sample after annealing, the carrier concentration was fitted to be $1.4 \times 10^{20} \text{ cm}^{-3}$. The carrier concentration decreased after annealing because of the incorporation of oxygen, which reduced the number of oxygen vacancies. This phenomenon led to a reduced free carrier concentration, making the ITO film less metallic and consequently less reflective in the IR spectral regime (with a corresponding increase of the IR emittance from 0.2 to ~0.4). It is to be noted that the structure was designed using pre-anneal parameters. We want to emphasize that carrier concentration obtained by theoretically fitting the reflectivity data over such a larger wavelength should be taken as a fitting parameter providing relative values as we assumed the relaxation time to be a constant (6.6 fs) and independent of the quality of our films in both pre and post annealing. In future studies we plan to independently validate this assumption for our films by performing independent electrical properties measurements. However we note that carrier concentration obtained by the fitting of the reflectivity data falls in the range of carrier concentrations observed in the literature (Tahar et al. 1998, Chen et al., 2010).

Comparing the theoretical and measured reflectance in Figure 2a, it can be observed that there is a relatively large difference between theory and measurement in the visible and NIR range, as compared with the IR range. This is because the transfer matrix model assumes that the absorber sample is specular when calculating the theoretical reflectance, however, the actual
sample is diffuse at short wavelengths with a surface roughness of around 200nm, making it comparable to the wavelength at shorter wavelengths (visible and NIR). This effect was not included in the optical modeling and is the reason for the difference between theoretical and measured reflectance at shorter wavelengths. Since, in the visible range, the ITO is transparent and most of the radiation is absorbed by the black chrome, the reflectance is close to zero both experimentally and theoretically. Other possible reasons for difference between theoretical and experimental data could be that: a) Refractive index of the black chrome was obtained by measuring the reflectivity of the bare black chrome and by applying the Kramers-Kronig relations. Its not clear if the properties of the black chrome particularly in the post annealing case will be different when covered with ITO. b) We assumed the relaxation time to be a constant and have taken its value from the literature (Chen et al., 2010) and assumed the carrier concentration to be a fitting parameter, which may also lead to some discrepancy between the model and data.

Figure 2: (a) Theoretical and measured near-normal (see Methods) hemispherical reflectance for the selective absorber before and after 800°C thermal annealing under ambient conditions. The
measurements were performed at room temperature with an incidence angle of 8° for 0.3–2.5 µm and 12° for 2.5–20 µm. (b) Average reflectance, lower and upper bound from 5 measurements.

To determine the uncertainty in our ambient measurements, we measured the hemispherical reflectance for the absorber sample five times. Based on the results, we calculated the standard deviation for the measurements. The lower and upper bounds for 95% confidential interval (1x standard deviation) are plotted in Figure 2b, along with the average reflectance measured from the five measurements. The repeatability of the reflectance measurement can be found to be very high.

3.2 Thermal Stability of SSA

As there is no industry standard on how many hours an SSA sample should be tested, we carried out the thermal cycling under two different process conditions. An overview of the thermal cycling can be found in Table 2.

<table>
<thead>
<tr>
<th>Sample</th>
<th>SSA-1</th>
<th>SSA-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ramp-up rate</td>
<td>20°C / min</td>
<td>20°C / min</td>
</tr>
<tr>
<td>Holding time</td>
<td>5 hours</td>
<td>10 hours</td>
</tr>
<tr>
<td>Temperature</td>
<td>800°C (60h), thereafter 900°C (60h)</td>
<td>800°C (120h)</td>
</tr>
<tr>
<td>Cooling</td>
<td>Furnace cooling</td>
<td>Furnace cooling</td>
</tr>
<tr>
<td>Reflectance measurement</td>
<td>After 3, 6, 12 cycles (15h, 30h, 60h) at each temperature</td>
<td>Every 20 hours</td>
</tr>
</tbody>
</table>

Table 2: Thermal cycling procedure for 2 samples of the suggested SSA structure

The first absorber sample (SSA-1) was thermally cycled at target temperatures of 800°C and 900°C for 3, 6, and 12 cycles (5 hours holding time), and then its near-normal hemispherical reflectance was measured. The following steps were used in each thermal cycle: the absorber was heated to the target temperature at a ramp-up rate of 20°C/min, held at the target temperature
for 5 hours, and then the furnace was cooled to room temperature. These steps were repeated for multiple thermal cycles. Therefore the SSA-1 was annealed for a total of 60 hours at 800°C and 60 hours at 900°C. The second absorber (SSA-2) was thermally cycled at 800°C for 120 hours with ramp-up rate of 20°C/min and holding time of 10 hours. SSA-2 was then furnace cooled and its near-normal hemispherical reflectance was measured after every 20 hours. The near-normal hemispherical reflectance values for both samples before and after thermal cycling are shown in Figure 3a)-c). The figures reveal only minor changes in the performance of the SSA, which exhibits an absorptance of 0.9 in the solar spectrum with an infrared (IR) emittance of 0.4 beyond wavelengths of 6 µm. When compared to other SSA designs for high temperatures (>700 °C) as shown in Table1, our proposed SSA design has shown stable performance under ambient conditions for maximum number of hours (120 hours). To investigate effect of temperature and time on black chrome, we conducted annealing experiments under similar test conditions for only black chrome. The results from both black chrome and selective solar absorber are shown in Figure 3d, which shows that the optical properties of black chrome and ITO are significantly different and selectivity is mostly due to ITO. This figure clearly shows that reflectivity is very low in visible and NIR primarily due to black chrome as it matches with the black chrome reflectivity whereas it’s high in IR due to ITO.
Figure 3: Optical performance of SSA-1 after thermal cycling at (a) 800°C and (b) 900°C. (c) Optical performance of SSA-2 after thermal cycling at 800°C. (d) Comparison of optical performance of black chrome and SSA-1 after thermal cycling showing the selectivity in IR is due to ITO.

Structural Characterization

Rutherford backscattering spectroscopy (RBS) analysis was performed before and after annealing to understand the effect of ambient annealing. The RBS spectra in Figure 4 reveals the presence of oxygen, silicon, tin, and indium atoms.
Figure 4: RBS spectra of selective absorber before and after annealing. RBS revealed oxygen intake after annealing.

The tin and indium atoms appear as one peak because of their very similar atomic masses. The broad peak from 100 to 600 keV can be attributed to the black chrome and substrate; the peak broadness stems from the large thicknesses of these layers. Comparison of the RBS spectra before and after annealing reveals two main differences. The first is that the amplitude of the oxygen peak increased (as observed in the zoomed-in inset), which suggests uptake of oxygen by the sample. We speculate that oxygen was incorporated into the ITO layer during the annealing process. However, only a small increase in the peak height was detected because the oxygen vacancy concentration in the ITO layer was small (Bellingham et al., 1991) compared with the concentration of existing oxygen atoms in ITO. The second major difference is that the intensity of the black chrome peak decreased at the higher-energy end but increased at the lower-energy end. The precise reason for this behavior is not clear. This difference could be explained by the lower energy of the helium ions scattered from deeper inside the layers, which means that the concentration of chromium atoms in the black chrome layer decreased at the layer surface but increased deeper inside the layer after annealing. This observation indicates the downward diffusion of chromium atoms resulting in lower concentration of Cr near the surface. These compositional changes in black chrome could be the potential reason for the minor reflectance change (~5%) in the visible/NIR spectral range. However more characterization studies are needed to exactly figure out the reason for this behavior. Similar changes in optical properties were observed in case of bare black chrome upon heat treatment (Smith, Mcphedran, & Derrick, 1985) where lower Cr concentration resulted in lower absorbance in visible/NIR range.
Imaging of the top surface of the sample before and after thermal cycling showed no significant changes, as shown in Figure 5.

Figure 5: SEM image of SSA-2 sample after a) annealing and b) 120 hours at 800°C, showing no significant changes on the surface.

3.3 Temperature-dependency of IR emittance

The previously mentioned reflectance measurements were all performed at room temperature after the annealing and thermal cycling. It was therefore worthwhile to explore the optical properties of the absorber at high temperatures, especially in the IR range, because the carrier concentration and relaxation time of ITO are affected by temperature, which will in turn affect its optical properties. Hence, the temperature dependent specular reflectance of the SSA-1 in the IR range was measured using an optical fiber coupled with an FTIR spectroscopy platform, as shown by one of the co-authors (Wang et al., 2015). Note that the high-temperature reflectance measurement setup only measures the specular component of the reflectance. As observed in Figure 6a, the measured specular reflectance is smaller than the measured hemispherical reflectance in Figure 3a, especially for shorter wavelengths. This difference occurs because the fabricated sample had a surface roughness of approximately 200 nm; therefore, the diffuse component for its reflectance was non-negligible at visible/NIR wavelengths. The surface
roughness was measured by a profilometer (Veeco, Dektak 150). We did not measure the temperature-dependent specular reflectance in the visible/NIR range because the sample was very diffuse at these wavelengths, and its specular reflectance was almost zero. However, the visible/NIR reflectance is mostly determined by the black chrome layer, and it has been previously shown that the optical properties of a Cr and Cr$_2$O$_3$ stack barely depends on temperature (Matsumoto and Tomita, 2010). Figure 6a presents the temperature dependent specular normal reflectance results for the annealed SSA-1 from room temperature to 800°C, conducted at the operating temperature. In general, the measured reflectance only slightly changed with temperature, with a variation within 10%. Figure 6b shows the reflectance at different temperatures for a wavelength of 15 µm. Interestingly, the measured reflectance remains almost constant from room temperature to 400°C, decreased slightly at 500°C, and then started increasing upon further increasing the temperature. This trend indicates that ITO becomes the least metallic/reflective at 500°C and starts to become more metallic upon further increasing the temperature. This finding implies a decreased carrier concentration at 500°C, which then starts to increase upon further increasing the temperature. The temperature-dependent resistance measured for annealed (first cycle) ITO by Gregory et al. (1995) is consistent with this behavior; in their work, the resistance of ITO increased at ~500°C and started to decrease beyond 600°C. However, it is to be noted after more number of cycles, Gregory et al. (1995) did not see this behavior. Hence more study will be needed to understand high-temperature behavior.
Figure 6. Operating temperature measurement of specular reflectance at normal incidence for the selective absorber (a) in the IR range and (b) at 15 µm.

4 Summary

In summary, we have designed and fabricated a high-temperature selective solar thermal absorber with ambient stability up to 900°C for 120 hours by utilizing a transparent conductive oxide layer and black chrome. High-temperature stability of the SSA up to 900°C and 120 hours was shown through thermal cycling, resembling the diurnal solar cycle (5 and 10 hours holding time). We also conducted IR reflectance measurements at various operating temperatures up to 800°C. The proposed solar absorber exhibited a solar absorptance of 0.9 in the solar spectrum and a thermal emittance of 0.4 (R = 0.6) in IR at wavelengths higher than 6 µm, which represents a great step forward in terms of spectral selectivity compared with Pyromark, the state of art for high-temperature solar absorbers with an IR emittance of ~0.85. To isolate effect of thermal cycling of underlying black chrome, we carried out thermal cycling of black chrome under similar annealing conditions and showed that the selectivity in IR is due to ITO. Future studies will aim at understanding the SSA behavior at temperatures higher temperature (>800°C) for
prolonged testing times under ambient conditions. These studies will include systematic investigation using in-situ TEM and (S)TEM of microstructural changes, oxidation and inter species diffusion in SSA such that a mechanistic model describing the rate of degradation as a function of temperature, time, and temperature cycling could be developed.

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6 Competing financial interests

The authors declare that they have no competing financial interests.

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