### 1. INTRODUCTION

The global energy crisis caused by the depletion of non-renewable resources and the serious environmental issues caused by the use of fossil fuels have led to an increase in the demand for renewable energy sources. In the current era of carbon neutrality, renewable energy technologies have attracted worldwide attention.\(^1\) The development and application of solar energy technologies have been actively promoted by various countries owing to their eco-friendliness and multiroute development, as well as flexible access to the abundant solar energy.\(^2\)\(^,\)\(^3\) There are two main technologies for harvesting solar energy, concentrating solar thermal (CST) and photovoltaic (PV), which facilitate the direct conversion of solar energy into heat and electricity, respectively.\(^4\)\(^-\)\(^6\) Although a CST system can convert the full solar spectrum into thermal energy, its efficiency in converting solar radiation into power after concentration is relatively low. This drawback has limited the development of CST systems.\(^7\) PV systems offer strong spectral selection characteristics; they generate electricity only in the visible to near-infrared (NIR) regions, and the rest of the spectral range is either lost or absorbed by the PV cell to generate heat.\(^8\) Therefore, to maximize the utilization of solar energy, a hybrid PV/CST system based on spectral beam splitting (SBS) has been proposed by numerous researchers.\(^9\)\(^-\)\(^11\) Components of such hybrid systems, must offer outstanding solar transmittance in the wavelength range of 300–1100 nm and maximized solar reflectance in the wavelength range of 1100–2500 nm.\(^9\)\(^-\)\(^11\)

Numerous studies have focused on the development of SBS films, which can be classified into two types: (i) interlaced high-refractive index and low-refractive index dielectric materials and (ii) metal/dielectric materials. Such films divide the solar spectrum into two parts: one in the wavelength range of 400–1100 nm for PV conversion and the other in the wavelength range of 1100–2500 nm for photothermal conversion, as illustrated in Figure 1. For example, Liang et al.\(^12\) prepared a SiO\(_2\)/TiO\(_2\) multilayer SBS film with a high average transmittance ($\tau \geq 96.8\%$) at 300–1100 nm and a high average transmittance ($\tau \geq 85\%$) at 1100–2500 nm. Other optical materials used for SBS films include Ge, Nb\(_2\)O\(_5\), Ta\(_2\)O\(_5\), and Na\(_3\)AlF\(_6\). Further, Wang et al.\(^13\) designed a multilayer SBS film consisting of 13 layers and reported an average transmittance of $\tau \geq 94\%$.\(^13\)
transmittance of 72.1% and a reflectance of 27.9% in the wavelength range of 250–2500 nm. In the past decade, various tandem multilayer films, such as SiO$_2$/TiO$_2$, Nb$_2$O$_5$/SiO$_2$, SiO$_2$/Ta$_2$O$_5$, Ge/SiO$_2$, SiN$_x$/SiO$_2$, and Ge/Nb$_2$O$_3$/Na$_3$AlF$_6$, have been utilized in hybrid CPV/ST or PV/CST systems. However, such coatings require strict control of the film thickness and the superimposition of multiple layers of various materials, which increase the complexity of processing SBS films. Therefore, single metal/dielectric coatings with intrinsic spectral selectivity have attracted considerable attention owing to their advantages such as simple processing, fewer film layers, and ease of control over the film thickness.

Currently, metal layers are being used as highly reflective layers for the infrared (IR) spectral range. However, there are only a few reports on their application in SBS films. Thin layers of Ag, Au, Cu, and other metals transmit visible and NIR wavelengths with intrinsic spectral selectivity have attracted considerable attention owing to their advantages such as simple processing, fewer film layers, and ease of control over the film thickness. To further analyze the optical performance of the SiN$_x$/Cu SBS film, the effects of the thicknesses of the SiN$_x$ and Cu layers as well as annealing conditions on the optical properties were examined in detail.

2.1. Structural Analysis. The microstructure of the SiN$_x$/Cu SBS film was investigated to determine its potential influence on the transmission and reflection characteristics. The schematic of the sputtering process in Figure 2a shows the substrate, targets, and working atoms. Argon (Ar) ions were

![Figure 1. Schematic of a hybrid system based on a spectral splitting film.](https://pubs.acs.org/doi/10.1021/acsomega.1c03178)

![Figure 2. (a) Pictorial representation of the magnetron sputtering process, (b) schematic of the SiN$_x$/Cu SBS film deposited on glass, (c) photograph of the SiN$_x$/Cu SBS film, and (d) cross-sectional morphology of the SiN$_x$/Cu SBS film.](https://pubs.acs.org/doi/10.1021/acsomega.1c03178)
generated by glow discharge in a vacuum environment and bombarded onto the target, and the ejected target material was deposited on the substrate to form a film. Figure 2b shows a schematic of the SBS film. The Cu layer was deposited directly.
on the BK7 glass substrate. Subsequently, the SiN$_x$ layer was deposited on the optimized Cu layer. **Figure 2c** shows a photograph of the reddish-brown SiN$_x$/Cu solar SBS film obtained by magnetron sputtering. The Cu layer is reddish-brown, while the SiN$_x$ layer is transparent. **Figure 2d** presents a cross-sectional SEM image of the SiN$_x$/Cu SBS film deposited on a Si substrate. The image shows the two distinct layers of the SBS coating and the columnar structure of the SiN$_x$ layer. The thicknesses of the Cu and SiN$_x$ layers were measured to be $\sim$17 and 67 nm, respectively.

**Figure 3a** shows the XRD pattern of the SiN$_x$/Cu solar SBS film on Si, along with that of the Si substrate. The XRD pattern of the sample is similar to that of the substrate, with minor differences in the $2\theta$ range of 30 to 35$^\circ$. The diffraction pattern of the SiN$_x$/Cu SBS film shows a weak peak at 32.3$^\circ$, which is enlarged in the inset of **Figure 3a**. This low-intensity peak corresponds to the (110) plane of Cu$_2$O and indicates that the Cu$_2$O phase was formed in the deposited film; similar results have been reported earlier. Another broad and weak peak is also observed at $\sim$45$^\circ$, corresponding to the (200) plane of Cu$_2$O in the XRD pattern of the deposited film. No strong diffraction peaks of Cu are observed because of its low content and poor crystallization. This result also implies good dispersion of the very small Cu agglomerates on the surface of the Si substrate. The rest of the diffraction pattern shows broad amorphous features, with no peaks indicative of crystalline phases. Thus, the XRD pattern reveals the presence of a thin Cu layer and the amorphous nature of the SiN$_x$ layer.

The microstructure and composition of the sample were further analyzed by EDS. **Figure 3b** shows the chemical composition of the SiN$_x$/Cu SBS film determined by microanalysis. Gold was spray-coated on the SiN$_x$/Cu SBS film sample to successfully perform the EDS analysis. The results indicate that the coating consists of silicon and copper. The silicon signal mainly originated from the Si substrate on which the SiN$_x$/Cu SBS film was deposited.

**Figure 3c** shows a three-dimensional (3D) AFM image of the SiN$_x$/Cu SBS film with a columnar structure. The film has a textured surface with a root-mean-square (rms) roughness of 1.06 nm (as determined using NanoScope Analysis software). The uniform, smooth, and dense surface of the SiN$_x$/Cu SBS film is evident in the SEM image in **Figure 3d**. Many gold particles (used for staining the sample) can be observed on the surface of the SiN$_x$/Cu SBS film, and there is no apparent
particle agglomeration at the scale of 200 nm in the SEM images. The AFM and SEM images indicate the formation of a uniform and dense sample surface, which is important for maintaining superior stability under long annealing times and also for preventing oxidation upon exposure to air.

2.2. Optical Properties. 2.2.1. Optimization of the Cu Layer. The Cu layer has high transmittance in the wavelength range of 300−1100 nm and high reflectance in the wavelength range of 1100−2500 nm, as shown in Figure 4. Figure 4a,b shows the transmittance and reflectance spectra of the single Cu layers recorded at different Ar flow rates and sputtering times, respectively. As the Ar flow rate increased, the maximum reflectance in the IR region and the transmittance in the visible region decreased, as shown in Figure 4a. However, the highest transmittance and reflectance were observed at an Ar flow rate of 22 sccm. To determine the effect of the layer thickness on the optical properties, the sputtering time of the Cu layer was varied between 40 and 60 s at the Ar flow rate of 22 sccm and a constant sputtering power. The highest transmittance and reflectance were achieved for the shortest sputtering time, as shown in Figure 4b. However, the Cu grains in the thinner Cu layer are known to agglomerate to form a discontinuous metal film, leading to severe light scattering. After a series experiments, an Ar flow rate of 22 sccm and a sputtering time of 40 s were used as the optimal sputtering parameters for the Cu layer.

The Cu layer thickness significantly affects the transmittance of the double-layer SiN/Cu SBS films in the visible and NIR regions of the solar spectrum. Furthermore, the overall effect of the thickness of the Cu layer on the transmission and reflection spectra is evident from Figure 4b. Figure 5a shows the transmittance and reflectance spectra of the SiN/Cu SBS films for different thicknesses of the Cu layer. It is clear that an increase in the thickness of the Cu layer (the sputtering time of the SiN layer was maintained) led to a distinct increase in the reflectance in the wavelength range of 780−2500 nm and a decrease in the transmittance in the visible region. As the Cu layer thickness increased, the cutoff wavelength shifted to a lower value. Considering the maximum transmittance in the visible range and the maximum reflectance in the IR range, the sputtering time of 40 s was chosen to be optimum for depositing the Cu layer on the double-layer SiN/Cu SBS film. 2.2.2. Optimization of the SiN Layer. The thickness of the SiN layer significantly affects the reflectance of solar energy in the IR region. Figure 5b shows the transmittance and reflectance spectra of the SiN layer prepared at different thicknesses. Increasing the thickness of the SiN layer (the Cu layer thickness was maintained) led to a distinct increase in the transmittance in the visible region and a decrease in the reflectance in the wavelength range of 780−2500 nm. As the SiN thickness increased, the cutoff wavelength shifted to a higher value because of the improved effect of SiN as an AR layer. As the maximum transmittance in the visible range and the maximum reflectance in the IR range were not significantly reduced, a sputtering time of 80 min was chosen to be optimum for the deposition of the SiN layer.

2.2.3. Spectral Properties of the SiN/Cu SBS Film. According to the above results, the thicknesses of the Cu and SiN layers significantly influence the transmittance and reflectance of the SBS film, respectively. Hence, we compared the optical properties of the SBS films with different Cu and SiN thicknesses and selected the best-performing film to carry out further spectral analysis. The optimized film consisted of a 17 nm thick Cu layer and 67 nm thick SiN layer and exhibited a maximum transmittance of 72.9% and a maximum reflectance of 89.7%. Figure 6 shows the transmittance and reflectance spectra of the Cu, SiN, and Cu/SiN films. The single layer of Cu shows intrinsic SBS characteristics, and the addition of the SiN layer improves the SBS characteristics owing to the decrease in the reflected light. Thus, the double-layer SiN/Cu SBS film exhibits a high average transmittance (τ = 54.8%) in the wavelength range of 380−1100 nm and a high average reflectance (ρ = 67.7%) in the ranges of 300−380 and 1100−2500 nm.

2.3. Thermal Stability. Different cooling systems have been proposed to ensure that the operating temperature of silicon PV cells is maintained below 50 °C. For the transmission of solar spectral wavelengths in the range of 300−1100 nm to the PV cell, the SiN/Cu SBS film was coated on the PV cell. Subsequently, the thermal stability of the SiN/Cu solar SBS films was evaluated to assess their operating lifetime at 50 °C, which is the maximum operating temperature of silicon PV cells. We analyzed the transmittance and reflectance spectra of the coatings annealed at 50 °C for different durations; the results are shown in Figure 7. In
general, structural changes that occur due to long annealing
times can lead to the attenuation of the optical properties of
materials. The optical properties of the SiN<sub>x</sub>/Cu solar SBS
film prepared in this study did not change significantly after
annealing. However, the maximum transmittance was reduced
from 73.4% to 68.9% after annealing at 50 °C for 168 h and
then increased to 71.8% after annealing for 360 h, as shown in
Figure 7a. The maximum reflectance was reduced from 89.7%
to 84.4% after annealing at 50 °C for 168 h and then increased
to 88.5% after annealing for 360 h, as shown in Figure 7b. The
variation of the optical efficiency of the film could be caused by
the inter-diffusion of Cu. Figure 8 displays the average
transmittance in the wavelength range of 380–1100 nm and
the average reflectance in the wavelength ranges of 300–380
and 1100–2500 nm after annealing. We mainly focus on the
trend of the average transmittance in the 380–1100 nm range
(black curve) and the average reflectance in the 1100–2500
nm range (red curve) in Figure 8a,b, respectively. The
transmittance and reflectance spectra fluctuate, rather than
showing a continuous monotonic trend with a long measure-
ment time. As the annealing time increased, the average
transmittance of the film initially decreased and then increased
after 168 h of annealing, as shown in Figure 8a. Evidently, the
average reflectance of the SiN<sub>x</sub>/Cu solar SBS films did not
change considerably after annealing for 360 h, as shown in
Figure 8b. These results suggest that the microstructure of the
SiN<sub>x</sub>/Cu solar SBS film is affected by the annealing duration,
resulting in a decrease in the maximum transmittance and
reflectance of the film.

SEM and AFM studies were performed to analyze the
reasons for the minimal spectral changes of the SiN<sub>x</sub>/Cu SBS
films annealed at 50 °C for different durations. As shown in
Figure 9a–f, the SiN<sub>x</sub>/Cu SBS films maintained a uniform,
smooth, and dense surface after annealing for different
durations. The high-magnification SEM images clearly show
the fine shape of the Ag particles (used for staining the sample)
with uniform shapes and flat surfaces. This indicates that the
surface morphology of the SiN<sub>x</sub>/Cu SBS films did not change
significantly after annealing at 50 °C for different durations.
Figure 10a–f shows the 3D AFM images of the annealed SiN<sub>x</sub>/
Cu SBS films, which display the surface microstructure in
detail. These are inconsistent with the two-dimensional SEM
images. The AFM images show a porous film with gradually
varying roughness; the rms roughness of the coatings

---

**Figure 7.** (a) Transmittance and (b) reflectance spectra of the SiN<sub>x</sub>/Cu SBS coatings annealed at 50 °C for different durations.

**Figure 8.** Variation in the (a) transmittance and (b) reflectance values of the coatings after annealing at 50 °C for different durations.
decreased from 1.07 (as-deposited) to 0.84, 0.80, 0.81, 0.78, and 0.69 after annealing for 10, 24, 96, 168, and 360 h, respectively. The surface structure of the coatings became denser with increasing annealing time. The increased rms roughness enhances the diffuse reflectance and decreases the transmittance. In brief, no significant changes were observed in the surface morphology of the coating, indicating excellent thermal stability of the films annealed at 50 °C for different durations (a high maximum transmittance of 71.8% and a reflectance of 88.5%). No diffusion of other atoms was observed in the coating at 50 °C. The long-term and high-temperature thermal stability of the SiN_x/Cu solar SBS film will be studied in the future.

3. CONCLUSIONS

A double-layer SBS film of SiN_x/Cu was prepared by magnetron sputtering. The SiN_x/Cu SBS film could divide the solar spectrum into two parts: one for PV conversion in the wavelength range of 300–1100 nm and the other for photothermal conversion in the wavelength range of 1100–2500 nm. To optimize the optical properties, the thicknesses of the metal and SiN_x layers were optimized by varying the sputtering power, sputtering time, Ar flow rate, and N_2 flow.
annealing for the attenuation of the optical properties was observed after with increasing annealing time. However, no significant widening of the wavelength range was realized by superimposing a SiN film with a maximum transmittance of 72.9% and a maximum reflectance of 89.7%. The XRD and EDS results confirmed the presence of Cu. The SiN/Cu SBS films became denser and showed fine Ag particles with uniform shapes and flat surfaces after annealing for different durations. The decreased rms roughness of the coatings led to decreased diffuse reflectance and increased transmittance. Thermal annealing studies indicated that the microstructure of the SiN/Cu solar SBS film evolved with increasing annealing time. However, no significant attenuation of the optical properties was observed after annealing for different durations. The coating annealed at 50 °C for 360 h exhibited a high transmittance of 71.8% and a reflectance of 88.5%. No diffusion of other atoms into the coating was observed. Thus, the SiN/Cu double-layer SBS film exhibits superior SBS properties and offers a new route for the development of PV/CST hybrid systems.

4. EXPERIMENTAL SECTION

4.1. Design. A novel double-layer SBS film of SiN/Cu was deposited on glass by magnetron sputtering. The thickness of the Cu film was set to ∼10–20 nm. A thick film decreases the transmittance of light, whereas a thin film (less than 10 nm) causes severe light scattering. This is because the atoms in thin films diffuse and form islands or a discontinuous metal film.32,33,36,37 The spectral splitting effect of the SBS film over a wider wavelength range was realized by superimposing a SiN film because it offers high transmittance in the wavelength range of 380–1100 nm and high reflectance in the rest of the solar wavelength range (300–2500 nm). A PV/CST hybrid system with the SiN/Cu SBS film was developed based on the linear Fresnel solar thermal technology, as illustrated in Figure 11. The SiN/Cu SBS film was placed on the PV cell, which is referred to as the PV mirror. In this system, the SiN/Cu SBS film can transmit light in the range of 300–1100 nm to the PV cell and reflect the rest of the solar energy to the solar receiver tube with a compound parabolic concentrator reflector. The PV mirrors can track the path of the sun and reflect sunlight to the solar receiver tube. Owing to the optical performance of the SiN/Cu SBS film, the PV mirror can produce more power.

4.2. Deposition. The SiN/Cu SBS films were deposited on BK7 glass (dimensions: 76.2 mm × 25.4 mm) or Si substrates using a magnetron sputtering system (Kurt J. Lesker, USA). The films deposited on glass substrates were used for studying the optical properties, while those deposited on Si substrates were used for structural and morphological analyses. Before placing the substrates in the vacuum chamber, they were cleaned with alcohol and deionized water in an ultrasonic agitator to remove grease and dust from the surface. High-purity Cu and Si targets (99.99%, diameter: 76.2 mm) were used for the film deposition.

The targets were pre-sputtered with Ar gas for 30 min to clean the surface before the experiment. After achieving a base pressure of 5.5 × 10⁻⁶ Torr, Ar gas was introduced into the chamber. The target current and voltage were stabilized, and the substrate shield was opened before starting the deposition. The Cu layer was deposited via non-reactive sputtering of the Cu target in a mixed gas atmosphere (Ar: 28 sccm; N₂: 25 sccm). The SiN layer was deposited by reactive sputtering of the Si target in a mixed gas atmosphere (Ar: 28 sccm; N₂: 25 sccm). The substrate was rotated to improve the uniformity of the film during sputtering.

Table 1. Deposition Parameters of the SiN/Cu SBS Film

| layer | sputtering method | gas flow rate (sccm) | target power density (W/cm²) | deposition time (min) | operating pressure (Pa) |
|-------|-------------------|----------------------|----------------------------|-----------------------|------------------------|
| Cu    | DC                | Ar 22 N₂ 0           | Cu 5.48 Si 0               | 1                     | 0.9                    |
| SiN   | RF                | Ar 28 N₂ 25          | Cu 3.29 Si 80             | 80                    | 1.3                    |

Figure 11. Schematic of a PV/CST hybrid system with an SBS film and a plot of the spectral irradiance of solar radiation and blackbody radiation.
Single-layer Cu and SiN<sub>x</sub> were deposited on BK7 glass substrates to study their optical properties, including the transmittance, reflectance, and cutoff wavelength. By optimizing the Ar flow rate, sputtering power, and sputtering time, a Cu layer with a high transmittance in the visible range and a high reflectance in the IR range was obtained. To optimize the solar selectivity of the SBS film, a SiN<sub>x</sub> layer was deposited on the optimized Cu layer by adjusting the N<sub>2</sub> flow rate, in addition to the other parameters. The optimized deposition parameters are presented in Table 1. Finally, a novel spectral splitting coating of SiN<sub>x</sub>/Cu was deposited on the BK7 glass substrate. The Cu and SiN<sub>x</sub> layers were deposited on BK7 glass substrates for different times at the same Ar flow rate and sputtering power to study the effect of the layer thickness on the transmittance and reflectance.

To study the thermal stability, the coatings were annealed at 50 °C in an incubator for different durations ranging from 10 to 360 h. The accuracy of the set temperature was ±0.2 °C. The structural and optical properties of the annealed films were evaluated after the films were cooled to ambient temperature.

4.3. Characterization. The reflection and transmission spectra of the SiN<sub>x</sub>/Cu SBS films in the solar spectral range (300–2500 nm) were obtained using a Cary 7000 UV/Vis/NIR spectrophotometer equipped with an integrating sphere (module 150 mm). The reflectance (ρ) and transmittance (τ) were calculated using Eqs 1 and 2, respectively,

\[
\rho = \frac{\int_{0.38 \mu m}^{1.0 \mu m} \rho(\theta, \lambda) I_0(\lambda) d\lambda + \int_{1.0 \mu m}^{2.5 \mu m} \rho(\theta, \lambda) I_0(\lambda) d\lambda}{\int_{0.38 \mu m}^{1.0 \mu m} I_0(\lambda) d\lambda + \int_{1.0 \mu m}^{2.5 \mu m} I_0(\lambda) d\lambda}
\]

(1)

\[
\tau = \frac{\int_{0.38 \mu m}^{1.0 \mu m} \tau(\theta, \lambda) I_0(\lambda) d\lambda + \int_{1.0 \mu m}^{2.5 \mu m} \tau(\theta, \lambda) I_0(\lambda) d\lambda}{\int_{0.38 \mu m}^{1.0 \mu m} I_0(\lambda) d\lambda + \int_{1.0 \mu m}^{2.5 \mu m} I_0(\lambda) d\lambda}
\]

(2)

where \(\lambda\), \(\rho(\theta, \lambda)\), \(\tau(\theta, \lambda)\), and \(I_0(\lambda)\) are the wavelength, the reflectance at a certain wavelength, the transmittance at a certain wavelength, and the direct normal solar irradiance, respectively, as defined according to ISO standard 9845-1 for normal irradiance and an air mass of 1.5. \(\rho\) and \(\tau\) are equally weighted fractions.

The surface features and fracture structure topography were studied by SEM (FV1000, Japan). EDS profiles of selected areas were recorded using an EDS instrument (FV1000, Japan). The surface morphology and roughness of the SBS coatings were investigated by AFM (ICON2-SYS Bruker Nano Inc.). The crystal structures of the as-deposited and annealed samples were studied by XRD (D8-Focus, Bruker AXS, Germany).

**AUTHOR INFORMATION**

**Corresponding Author**

Dongqiang Lei — Key Laboratory of Concentrating Solar Thermal Energy and Photovoltaic System, Chinese Academy of Sciences, Beijing 100190, China; Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100190, China; University of Chinese Academy of Sciences, Beijing 100049, China; Beijing Engineering Research Center of Concentrating Solar Thermal Power, Beijing 100190, China; Phone: +86-132-4045-8306; Email: ldqjimei@126.com

**Authors**

Xin Zhang — Key Laboratory of Concentrating Solar Thermal Energy and Photovoltaic System, Chinese Academy of Sciences, Beijing 100190, China; Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100190, China; University of Chinese Academy of Sciences, Beijing 100049, China; Beijing Engineering Research Center of Concentrating Solar Thermal Power, Beijing 100190, China; orcid.org/0000-0003-0668-8400

Bo Zhang — North University of China, Taiyuan, Shanxi 030051, China

Pan Yao — Key Laboratory of Concentrating Solar Thermal Energy and Photovoltaic System, Chinese Academy of Sciences, Beijing 100190, China; Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100190, China; University of Chinese Academy of Sciences, Beijing 100049, China; Beijing Engineering Research Center of Concentrating Solar Thermal Power, Beijing 100190, China

Zhifeng Wang — Key Laboratory of Concentrating Solar Thermal Energy and Photovoltaic System, Chinese Academy of Sciences, Beijing 100190, China; Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100190, China; University of Chinese Academy of Sciences, Beijing 100049, China; Beijing Engineering Research Center of Concentrating Solar Thermal Power, Beijing 100190, China

**Complete contact information is available at:**

https://pubs.acs.org/10.1021/acsomega.1c03178

**Notes**

The authors declare no competing financial interest.

**ACKNOWLEDGMENTS**

This work was funded by the National Key R&D Program of China (no. 2019YFE0102000).

**REFERENCES**

(1) Zhao, N.; Fengqi, Y. Can Renewable Generation, Energy Storage and Energy Efficient Technologies Enable Carbon Neutral Energy Transition? Appl. Energy 2020, 279, 115889.

(2) Liang, H.; Wang, F.; Cheng, Z.; Xu, C.; Li, G.; Shuai, Y. Full Spectrum Solar Energy Utilization and Enhanced Solar Energy harvesting via Antireflection and Scattering Performance Using Biomimetic Nanophotonic Structure. ES Energy Environ. 2020, 8, 29–41.

(3) Kumar, L.; Hasanuzzaman, M.; Rahim, N. A. Global Advance- ment of Solar Thermal Energy Technologies for Industrial Process Heat and Its Future Prospects: A Review. Energy Convers. Manage. 2019, 195, 885–908.

(4) Hjerrild, N. E.; Scott, J. A.; Amal, R.; Taylor, R. A. Exploring the effects of heat and UV exposure on glycerol-based Ag–SiO<sub>2</sub> nanofluids for PV/T applications. Renewable Energy 2018, 120, 266–274.

(5) Yazdanifard, F.; Ameri, M. Exergetic Advancement of Photovoltaic/Thermal Systems (PV/T): A Review. Renewable Sustainable Energy Rev. 2018, 97, 529–553.

(6) Wang, G.; Yao, Y.; Wang, B.; Hu, P. Design and Thermodynamic Analysis of an Innovative Hybrid Solar PV-CT System with Multi-Segment PV Panels. Sustain. Energy Technol. Assess. 2020, 37, 100631.

(7) Widyolar, B.; Lun, J.; Jia, B.; Rwa, B.; Ak, C.; Mo, C.; De, D.; Ha, D. Theoretical and Experimental Performance of a Two-Stage (S0X) Hybrid Spectrum Splitting Solar Collector Tested to 600°C. Appl. Energy 2019, 239, 514–525.

(8) Zhang, G.; Wei, J.; Xie, H.; Wang, Z.; Xi, Y.; Khalid, M. Performance Investigation on a Novel Spectral Splitting Concentrat-
ing Photovoltaic/Thermal System Based on Direct Absorption Collection. Sol. Energy 2018, 163, 552–563.
(9) Huang, G.; Curt, S. R.; Wang, K.; Markides, C. N. Challenges and Opportunities for Nanomaterials in Spectral Splitting for High-Performance Hybrid Solar Photovoltaic-Thermal Applications: A Review. Nano Mater. Sci. 2020, 2, 183–203.
(10) Wang, G.; Yao, Y.; Lin, J.; Chen, Z.; Hu, P. Design and Thermodynamic Analysis of a Novel Solar CPV and Thermal Combined System Utilizing Spectral Beam Splitter. Renewable Energy 2020, 155, 1091–1102.
(11) Wei, D.; Cao, F.; Wu, Z.; Liu, Y.; Wang, J.; Wang, Q.; Liu, X.; Zhang, Q. Enhanced Spectral Splitting in a Novel Solar Spectrum Optical Splitter Based on One Dimensional Photonic Crystal Heterostructure. J. Materiomics 2021, 7, 648–655.
(12) Liang, H.; Han, H.; Wang, F.; Cheng, Z.; Lin, B.; Pan, Y.; Tan, J. Experimental Investigation on Spectral Splitting of Photovoltaic/Thermal Hybrid System with Two-Axis Sun Tracking Based on SiO2/TiO2 Interference Thin Film. Energy Convers. Manage. 2019, 188, 230–240.
(13) Wang, G.; Yao, Y.; Chen, Z.; Hu, P. Thermodynamic and Optical Analyses of a Hybrid Solar CPV/T System with High Solar Concentrating Uniformity Based on Spectral Beam Splitting Technology. Energy 2019, 166, 256–266.
(14) Imenes, A. G.; Buie, D.; McKenzie, D. The Design of Broadband, Wide-Angle Interference Filters for Solar Concentrating Systems. Sol. Energy Mater. Sol. Cells 2006, 90, 1579.
(15) Jiang, S.; Hu, P.; Mo, S.; Chen, Z. Optical Modeling for a Two-Stage Parabolic Trough Concentrating Photovoltaic/Thermal System Using Spectral Beam Splitting Technology. Sol. Energy Mater. Sol. Cells 2010, 94, 1686–1696.
(16) Jiang, S.-L.; Peng, H.; Mo, S. P.; Chen, Z.-S. Modeling for Two-Stage Dish Concentrating Spectral Beam Splitting/Photovoltaic-Thermal System; IEEE, 2009.
(17) Esler, C.; Flowers, C.; Warmann, E.; Lloyd, J.; Espinet-González, P.; Darbe, S.; Dee, M.; Escarra, M.; Kosten, E.; Zhou, W.; Atwater, H. The Polyhedral Specular Reflector: A Spectrum-Splitting Multijunction Design to Achieve Ultrahigh (>50%) Solar Module Efficiencies. IEEE J. Photovolt. 2018, 9, 174–182.
(18) Wang, G.; Wang, B.; Yao, Y.; Lin, J.; Chen, Z.; Hu, P. Parametric Study on Thermodynamic Performance of a Novel PV Panel and Thermal Hybrid Solar System. Appl. Therm. Eng. 2020, 180, 115807.
(19) Crisostomo, F.; Taylor, R. A.; Zhang, T.; Perez-Wurfl, L.; Rosengarten, G.; Everett, V.; Hawkes, E. R. Experimental testing of SINx/SiO2 thin film filters for a concentrating solar hybrid PV/T collector. Renewable Energy 2014, 72, 79–87.
(20) Sibin, K. P.; Selvakumar, N.; Kumar, A.; Dey, A.; Sridhara, N.; Shashikala, H. D.; Sharma, A. K.; Barshilia, H. C. Design and Development of ITO/Ag/ITO Spectral Beam Splitter Coating for Photovoltaic-Thermoelectric Hybrid Systems. Sol. Energy 2017, 141, 118–126.
(21) Wang, L.; Shen, Z.; Du, G.; Wang, P.; Wang, P. The Thermal Stability of Silver-Based High Reflectance Coatings. Thin Solid Films 2016, 616, 122–125.
(22) Li, F.; Zhang, Y.; Wu, C.; Lin, Z.; Zhang, B.; Guo, T. Improving Efficiency of Organic Light-Emitting Diodes Fabricated Utilizing AZO/Ag/AZO Multilayer Electrode. Vacuum 2012, 86, 1895–1897.
(23) Zhu, B. L.; Ma, J. M.; Lv, K.; Wang, C. J.; Wu, J.; Gan, Z. H.; Liu, J.; Shi, X. W. Improvement of Transparent Conductive Properties of GZO/Cu/GZO Tri-Layer Films by Introducing H2 into Sputtering Atmosphere. Superlattices Microstruct. 2020, 140, 106456.
(24) Du, M.; Lei, H.; Jing, M.; Fang, L.; Liu, X.; Jiang, L.; Wang, S. Optimization Design of TiO2/SnO2/TiO2SnO2/AlN Coating Used for Solar Selective Applications. Sol. Energy Mater. Sol. Cells 2011, 95, 1193–1196.
(25) Guo, H.-X.; Yu, D.-M.; He, C.-Y.; Qiu, X.-L.; Zhao, S.-S.; Liu, G.; Gao, X.-H. Double-Layer Solar Absorber Coating Based on High Entropy Ceramic AlCrMoTaTiN Structure, Optical Properties and Failure Mechanism. Surf. Interfaces 2021, 24, 101062.