SPECIAL TOPIC: Graphene Oxides towards Practical Applications

Sponge-templating synthesis of sandwich-like reduced graphene oxide nanoplates with confined gold nanoparticles and their enhanced stability for solar evaporation

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ABSTRACT Solar evaporation based on plasmonic metal nanoparticles (MNPs) is emerging as a promising technology. However, the fine structure of MNPs is unstable, and both the high temperature generated by intensive light and corrosive ions in water could damage them. The performance will decline after recycling and long-time usage. To address these issues, we adopted a sponge-templating method for preparing sandwich-like nanoplates with the gold nanoparticles (Au NPs) confined in reduced graphene oxide (rGO) nanosheets. Due to the confinement effect, both the surface melting and ion diffusion were suppressed. The solar evaporator based on the sandwich-like nanoplates showed a high solar-vapor conversion efficiency of 85.2% under a high light intensity of 10 kW. After 30 times recycle of seawater desalination, the conversion efficiency scarcely decreased. These sandwich-like nanoplates with enhanced thermal and chemical stability of Au NPs are promising in the practical application of seawater desalination.

Keywords: sponge template, confinement effect, surface melting, desalination

INTRODUCTION

Solar evaporation is emerging as one of the most promising solar-thermal technologies that can be applied in concentrating solar power [1,2], water desalination [3–7], and sewage treatment [8]. Various solar-thermal materials have been developed, including plasmonic metallic nanoparticles (MNPs) [3,7,9,10], carbon materials [4,11], and metal oxide composites [8,12]. With the localized

surface plasmon resonance (LSPR) of MNPs, the temperature around MNPs will rise drastically, making MNPs ideal solar-thermal conversion materials [3,9]. However, these MNPs are usually unstable under conditions of solar concentrating and sewage dipping [1]. The high temperature generated by intensive light will melt the MNPs [10], and the corrosive media in water like acid, alkali, and salt will etch the MNPs [13], which limit their durability and cycling performance. Therefore, the thermal and chemical stabilities are crucial for the performance of MNPs-based solar evaporators.

The nanometer-scale MNPs are quite unstable compared with bulk materials [14,15]. Due to the high surface/volume ratio, surface atoms account for a large proportion of MNPs. The surface atoms are usually far from equilibrium state due to the lack of adjacent atoms. There exist many dangling bonds that tend to combine with other atoms, resulting in the chemically active surface for MNPs [16]. Besides, based on the study of semi-infinite Einstein model crystal [17], the surface atoms become unstable at the melting temperature much lower than bulk lattice, and the so called surface melting effect has been observed [18]. During the surface melting process, a liquid layer of the first few atomic layers will form surrounding a rigid metal core [19]. The MNPs usually undergo shape transformation, and the adjacent MNPs would melt and form big aggregates [19–21].

Meanwhile, the confinement effect may provide a platform to address the above problems [22–25]. Below a critical length scale of confined space, the depression of

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melting point theory based on continuum thermodynamics and the Gibbs-Thomson effect is no longer applicable [26]. For instance, unusual high melting point has been observed for phase transitions within nano-sized carbon nanotubes (CNTs) [27]. Based on this confinement effect, thermally stable nanocatalysts for high-temperature reactions have been developed. Au nanoparticles (NPs), and Pt NPs are confined by various porous hosts such as ligands, mesoporous silica (SBA-15), and mesoporous carbon [22,23,25]. The surface melting temperatures of those confined NPs are obviously higher than the unconfined ones [22]. The size, shape and composition of pristine NPs are maintained after high-temperature reactions, providing the possibility to carry out many important catalytic processes [23].

Besides, the confinement effect may isolate the MNPs from the diffusion of ions if the porous host is replaced with impermeable materials. Defect-free and monolayer graphene is considered as an ideal impermeable barrier against the diffusion of ions and gas [28,29]. In practical, defective graphene oxide (GO) or reduced GO (rGO) is usually used in multilayer stacking manner to obtain excellent barrier properties. The stacking structure, which provides a long, tortuous path for ion diffusion, is a crucial factor affecting the barrier properties. The size of GO or rGO nanosheets and film thickness influence the tortuosity. For nanosheets of 5 μm , the diffusional path is 1300 times longer than the film thickness. Horizontally, highly interlocked, stacked graphene structures may maximize the tortuosity [30], which significantly decrease the ion diffusion through layered films. Some studies have used graphene as metal protecting layers to prevent the oxidation, corrosion, and degradation in electrochemical systems [31,32].

Herein, we designed and synthesized a kind of sandwich-like nanoplates (rGO/Au NPs/rGO) by a programmable decoration method using melamine sponge (MS) as a sacrificial template. Precise construction of the spatial structures brought structural property different from previous graphene composite [33]. We found that the Au NPs confined in the multilayered rGO sheets could suppress both the surface melting and ion diffusion, enhancing the thermal and chemical stability at the same time. Sandwiched Au NPs confined in rGO interlayers could maintain the original isolated state even at 500°C, while the unconfined Au NPs would melt and fuse into aggregates at 120°C. Meanwhile the rGO sheets could protect the Au NPs from chemical etching by KI/I_2 solution. What's more, graphene could enhance the photothermal conversion efficiency of MNPs [34]. The

nanoplates were applied as the light absorption layer for solar seawater desalination. Under high solar flux of 10 kW, the solar evaporator showed stable performance in etching solution during sea water desalination. The solar-vapor conversion efficiency could reach 85.2% under 10 kW. After 30 times cycling, no obvious performance decrease was observed compared with the unconfined control group.

EXPERIMENTAL SECTION

Materials

Silane coupling agent KH550 was purchased from Shanghai Yaohua (China). Other reagents were purchased from Sinopharm Chemical Reagent Co., Ltd. (China), and were used directly without any further purification. KI/I_2 solution was prepared by dissolving 3.5 g I_2 and 7 g KI into 50 mL deionized water (DIW). Seawater collected from Gulf Stream in the Gulf of Mexico was purchased from Sigma-Aldrich (USA).

Instruments

Scanning electron microscopy (SEM) images were obtained from a Zeiss Supra 40 scanning electron microscope at an acceleration voltage of 5 kV. Transmission electron microscopy (TEM) was performed on H-7650 (Hitachi, Japan) at an acceleration voltage of 100 kV. Ultraviolet-visible-near infrared (UV-Vis-NIR) spectra were collected on a UV-Vis-NIR spectrophotometer (SOLID3700), and the solar absorption (A) was calculated using the equation of $A = 1 - T - R$, where T and R were calculated using the integral average method [35]. The water contact angle (CA) was measured using the sessile drop method by OCA25 (DataPhysics Instruments GmbH, Germany) at the moisture of 52% and temperature of 27°C. The drop volume was 3 μL . Freeze drying was carried out using a freeze drier (Labconco-195). IR images and movie were taken by an IR Camera (VarioCAM hr head). The simulated light was generated from 300 W Xe lamp (Beijing Perfectlight, PLS-SXE300c). The light was focalized by Fresnel lens to obtain the high light intensity. Electronic analytical balance (Mettler Toledo, AL104, RS323 data cable) connected to a computer was used to record the weight change.

Synthesis of sandwich-like rGO/Au NPs/rGO nanoplates

Au NPs, GO coated melamine sponge (MS) (MS@GO), and MS@GO/Au NPs were firstly prepared as described in Supplementary information. Then, 6 mg mL^{-1} GO solution was diluted with alcohol to a concentration of

3 mg mL⁻¹. MS@GO/Au NPs were dipped into the diluted 3 mg mL⁻¹ GO solution and centrifuged at 2000 r min⁻¹ for 2 min. After drying at 85°C, MS@GO/Au NPs/GO was obtained. MS@GO/Au NPs/GO was dipped into 35 mL of 0.3 mol L⁻¹ HCl solution and heated at 120°C for 6 h to remove the MS, and then the reactor cooled down naturally. The aerogels dipped in DIW were freeze-dried in vacuum by a Labconco FreeZone 6 freeze dryer, and the rGO/Au NPs/rGO aerogels were obtained. Finally, the freeze-dried aerogels were dipped into 5 mL of ethanol solution and crushed under ultrasonic for 5 min to obtain the final dispersion.

RESULTS AND DISCUSSION

Porous MS was used as the sacrificial template in substrate engineering approach for the preparation of sandwich-like nanoplates [33,36]. As shown in Fig. 1, MS@GO was firstly prepared. The multilayered GO nanosheets were laterally stacked on the skeleton of MS. Then, Au NPs of ~40 nm were assembled on the GO layer, and another layer of GO was coated to seal the Au NPs (Fig. S1). Finally, MS was removed and GO was reduced to obtain rGO/Au NPs/rGO nanoplates (Fig. S2). Commercial sponges are readily available and low-cost bulk templates, considering the large specific area and high templating efficiency. We also found that the GO sheets were horizontally stacked on the surface, forming a concentric structure. This is because the lateral size of GO sheets is larger than the skeleton of MS. Under an external shear force, the GO sheets tend to attach on the substrate in this manner. Besides, this sequential method

Figure 1 Schematic illustration of the preparation of sandwich-like nanoplates using MS as the sacrificial template. The sequential process consists of template-directed assembly, template-removal, and crush. And the solar evaporator was fabricated using the sandwich-like rGO/Au NPs/rGO nanoplates as the light absorption layer.

generates obvious sectional structure, i.e., the sandwich-like structure [37].

The MS@GO was prepared *via* a crucial centrifugation-assisted dip coating method [36]. GO solution (3 mg mL⁻¹) penetrated MS bulk was centrifuged at 2000 r min⁻¹. Excess GO could be removed and the bulk turned light yellow (Fig. S2a). The GO coating was stacked laterally on the MS skeleton without blocking pores as shown in Fig. 2a. This method could be classified into flow-based system besides immersive and spray coating for 3D porous substrate coating [33,38]. Reynolds number (R_{ed}) was used to explain the GO flow [39]. A suitable speed (2000 r min⁻¹) was important. When the centrifugation speed was too small, the flow could hardly overcome the viscosity of GO. When the centrifugation speed was too fast, the R_{ed} would increase to stagnation point, and the films would grow on the back of the cylinders, resulting in blocking pores.

To prepare MS@GO/Au NPs, MS@GO needs to be firstly modified by 3-aminopropyltriethoxysilane (KH550), because Au NPs are negatively charged due to the surfactant layer of citric acid. Then the modified MS@GO was dipped into the Au NPs solution, and the Au NPs distributed uniformly on the surface *via* the electrostatic-assisted assembly (Fig. S2b, c). Another GO layer on MS@GO/Au NPs was coated to seal the Au NPs

Figure 2 SEM images of MS@GO (a), MS@GO/Au NPs/GO (b), and sandwich-like rGO/Au NPs/rGO nanoplates after MS removal and crush (c).

via the same centrifugation-assisted dip coating method. As shown in Fig. 2b, the Au NPs were still maintained and covered by the outer GO layer. Due to the flexibility and strong van der Waals forces of GO sheets, Au NPs were sealed in disconnected chambers, forming MS@GO/Au NPs/GO. Then, the sample was immersed in water under hydrothermal condition at 120°C to remove the MS. As shown in Fig. S2d, after hydrothermal treatment and freeze drying, black aerogels with ~50% volume shrank could be obtained, revealing the GO was reduced into rGO meantime. As shown in Fig. S2e, the hydrolysis process did not damage the structure of rGO layer, and the distorted hollow tubular structure was revealed in Fig. S2f. The aerogels could easily be crushed under sonication, resulting in the final sandwich-like nanoplates with ~20 μm lateral size (Fig. 2c). And the monodispersed Au NPs sealed between the crumpled rGO interlayers were easy to be seen.

Solid state Au NPs would undergo shape transformation at a temperature much lower than the bulk melting point (1064°C) due to the surface melting effect [18]. We found that the thermal stability of Au NPs in the sandwich-like rGO/Au NPs/rGO nanoplates was improved. MS@rGO/Au NPs/rGO and MS@rGO/Au NPs were heated at 100, 120, 150, 180, and 500°C for 2 h. At 100°C, the two samples maintained the original state. Increasing the temperature to 120°C, the adjacent Au NPs began to melt and fused into dimer, trimer, and so on as shown in Fig. 3c, indicating the occurrence of surface melting. At 140°C, interparticle diffusion and subsequent agglomeration occurred. The agglomerates were in irregular shape, indicating the rigid metal core was still maintained (Fig. 3d). When heated at 180°C in argon atmosphere, the agglomerates of Au NPs were spherical, and the size of individual Au NPs was larger than the original ones (Fig. 3e). In contrast, MS@rGO/Au NPs/rGO could suppress the surface melting of Au NPs. The distribution density of Au NPs was smaller due to the detachment during the centrifugation process as shown in Fig. 2b. When heated at 180°C, the sandwiched Au NPs maintained the original monodispersing state as shown in Fig. 3f. When heated at 500°C in argon atmosphere, Au NPs were still confined in the rGO chambers, while the agglomerates in chambers melted into spheres (Fig. 3g and Fig. S3a). Au NPs would diffuse and merge above the melting temperature when confined in mesoporous silica (SBA-15) [22]. For our sandwich-like nanoplates, the diffusion of Au NPs did not occur due to the barrier of rGO sheets. The number of rGO chambers determined the number of individual Au NPs. The Au NPs confined

Figure 3 (a) Asymmetric decorated rGO/Au NPs nanoplates. (b) The amphipathic rGO/Au NPs nanoplates film at the hexane/water interface. The two sides of rGO/Au NPs film had different water CAs. SEM images of MS@rGO/Au NPs after heating at 120°C (c), 140°C (d), and 180°C (e). SEM images of MS@rGO/Au NPs/rGO after heating at 180°C (f) and 500°C (g). (h) Fractions of the individual Au NPs after heating at temperatures from 100 to 180°C.

in chambers still maintained the original state, demonstrating the obvious improvement of thermal stability. Further, we counted the fraction of individual Au NPs compared with their original state to evaluate the effects of surface melting. The agglomerate was counted as one. The fraction at high temperature (500°C) was not counted because the unconfined Au NPs had been totally melted. As shown in Fig. 3h, the fraction of unconfined Au NPs decreased to 38% obviously at 120°C, and finally decreased to 16% at 180°C. For the Au NPs confined in the interlayer of rGO, the fraction of individual Au NPs at 120°C was 71%, and then became stable as the temperature increased. Finally, the fraction of single Au NPs decreased to 64% at 180°C. In fact, at higher temperature

of 500°C, the fraction of individual Au NPs in the sandwiched nanoplates still maintained ~60%.

rGO nanosheets are hydrophobic, and the particle decoration could change the wettability [40]. As shown in Fig. 3a, the Au NPs decorated on the backside of bare rGO nanoplates. When the dispersion of rGO/Au NPs was dropped into a layered hexane/water mixture, the nanoplates would immediately form a black film on the interface (Fig. 3b). After vigorous stirring, a black film would recover spontaneously, with no black residues in hexane or water. Then, the film was transferred onto a glass slide *via* a one-step or two-step process to expose the either side (Fig. S4). The CA of the hydrophilic side was 73.8°, while that of the hydrophobic side was 133.6° as shown in Fig. 3b, demonstrating the wettability difference. However, for the sandwich-like rGO/Au NPs/rGO nanoplates, the films were totally hydrophobic after hydrazine hydrate reduction. By slightly shaking a drop of water in hydrophobic powder, the so called “liquid marbles” could form.

Besides, the chemical stability was enhanced due to the physical isolation effect of rGO chamber. Common KI/I₂ solution was used for etching gold in MS@rGO/Au NPs and MS@rGO/Au NPs/rGO. The unconfined Au NPs were easily etched at a low concentration of 2 wt%, leaving the bare rGO surface (Fig. S3b). While the rGO-confined Au NPs were still maintained after etching by the same solution (Fig. S3c). It is noted that the rGO chamber was composed of multilayered rGO sheets. After reduction, the interlayer of rGO was graphitized, which provided an effective physical barrier to prevent the diffusion of ions in the solution.

As shown in Fig. 4a, the rGO/Au NPs/rGO nanoplates were filtered onto a filter paper, forming a uniform and black rGO/Au NPs/rGO nanoplates film (NPF). In Fig. 4b, an SEM image showed that the wrinkled nanoplates were filled in the blank space and attached on the disordered cellulose fibrils randomly. The rough surface could reduce light reflection and enhance the light absorption. Hydrazine hydrate-reduced GO sheets were filtered as control as shown in Fig. S3d. The bright light reflection was obvious when the film was bended. The UV-Vis-NIR test was conducted to evaluate the light absorption of the two films. As shown in Fig. 4c, the absorption of paper-rGO/Au NPs/rGO nanoplates was ~91% while the absorption of paper-rGO was ~85%.

Enhanced photothermal conversion efficiency by adding Au NPs in rGO has been demonstrated [34,41]. An IR camera after calibration was used to measure the surface temperature and temperature distribution of the NPF

Figure 4 (a) Sandwich-like rGO/Au NPs/rGO NPF filtered on the filter paper. (b) The rough surface of the NPF. (c) Measured absorption spectra of the NPF and filter paper-rGO. The max temperature and temperature distribution of the NPF under different light intensities of 1 kW (d), 5 kW (e), and 10 kW (f).

under different light intensities. The highest temperatures of the samples were recorded under different light intensities of 1, 5, and 10 kW m⁻². The maximal temperature appeared on the center of the film due to the heat dissipation to air on the edge as shown in Fig. 4d–f. The maximal temperatures were 75.5, 175.4, and 266.9°C under 1, 5 and 10 kW m⁻² respectively. Under 10 kW m⁻², the rGO began to be oxidized in the air reaching the limit of high temperature. The rGO/SiO₂/rGO and rGO/Au NPs based films were prepared as control. The maximal temperatures of the samples are listed in Table S1. The temperature for rGO/Au NPs/rGO was a little higher than that of rGO/SiO₂/rGO under 1 kW m⁻². While the difference became larger, reaching ~10°C under 5 kW m⁻². Under 10 kW m⁻², the maximal temperatures of the three samples were all over 260°C. The temperature was high enough to oxidize the rGO in the air, so the maximal temperatures were almost the same. The rGO/Au NPs/rGO group could reach the highest temperature among the three groups under different light intensities, demonstrating that the synergistic effect of Au NPs and rGO led to higher photothermal conversion efficiency [34].

The NPF was applied as the light absorption layer in a solar evaporator under high light intensity for desalination. As shown in Fig. 1, the solar evaporator was fabri-

cated according to the reported layered structure [10]. The thermal insulating foam with closed pores was placed to impel the heat conduction to water. Hydrophilic cotton wick array was penetrated throughout the foam. The capillary force of cotton and filter paper would channel the water to NPF for evaporation.

The original water temperature was 23.3°C (Fig. S5a). After being illuminated for 15 min under 10 kW m⁻², the maximal temperature of 50 mL water increased to 56.7°C (Fig. S5b). In contrast, the maximal temperature of the solar evaporator with NPF reached 85.4°C (Fig. 5a). Besides, the heating process of the solar evaporator was very fast, and obvious water vapor could be observed on the top of the solar evaporator (inset in Fig. 5a). The temperature increased to the balance temperature of ~85°C in

100 s. The evaporation efficiency (η_{ep}) was used to evaluate the light-to-heat conversion performance [3], defined as

$$\eta_{\text{ep}} = \frac{\dot{m} h_{\text{LV}}}{P_{\text{in}}}, \quad (1)$$

where $\dot{m}$ denotes the mass flux (slope of the weight change), h_{LV} denotes the total enthalpy of liquid-vapor phase change (sensible heat + phase-change enthalpy), and P_{in} is the light power density.

The weight change of water as a function of time was recorded in Fig. 5b. When the loading mass of Au NPs/rGO/Au NPs nanoplates in NPF increased from 0 to 0.45 mg cm⁻², the weight change of water in 1 h increased obviously from 4.32 to 12.12 kg m⁻², corresponding to η_{ep} of 30.3% and 85.2% under the light intensity of

Figure 5 (a) The curve of maximal temperature on the evaporator surface. Inset shows that steam was obvious on the top of solar evaporator. (b) The water weight changes along time for the rGO/Au NPs/rGO nanoplates with different Au NPs loadings. Evaporation of different samples under one sun (c) and 10 kW m⁻² light intensity (d). (e) The measured concentrations of five primary ions in an actual seawater (Gulf of Mexico) before and after desalination. (f) Cycling performance of the rGO/Au NPs/rGO nanoplates and rGO/Au NPs nanoplates.

10 kW m⁻², respectively. When the loading mass was 0.45 mg cm⁻², the filter paper presented totally black. In contrast, the rGO/SiO₂/rGO nanoplates templated by the same amount of MS showed a lower η_{ep} of 81.4%, according to the evaporation rate of 11.58 kg m⁻² h⁻¹ under 10 kW m⁻² (Fig. 5d). Solar evaporation performance under the light intensity of 1 kW m⁻² was also measured. The calculated η_{ep} were 72.5%, 70.21%, 66.61% and 63.35% for rGO/Au NPs/rGO, rGO/SiO₂/rGO, rGO/Au NPs and rGO, respectively. These results indicate the enhancement of photothermal conversion efficiency of rGO/Au NPs/rGO nanoplates. Compared with other gold-based or plasmonic absorbers, the NPF also shows good evaporation rate and efficiency (Table S2).

Sterile-filtered seawater collected from the Gulf Stream in the Gulf of Mexico was used for desalination. Concentrations of five primary ions before and after desalination were tested by inductively coupled plasma atomic emission spectrometer (ICP-AES), including Na⁺, Mg²⁺, Ca²⁺, K⁺, B³⁺. As shown in Fig. 5e, the ion concentrations after desalination were obviously reduced. For instance, the concentration of Na⁺ decreased from 10,940 to 18.55 mg L⁻¹, far below the salinity levels of direct drinking water defined by World Health Organization (salinity: 103 mg L⁻¹). After long time desalination for 3 h under 5 kW m⁻², white salt crystals appeared on the surface of the NPF (Fig. S5c). This salt accumulation phenomenon would deteriorate the light absorbing and water transportation. Fortunately, this problem could be solved by avoiding continuous desalination at high intensity, or physical cleaning. Compared with the integrated device of bulk materials, physical cleaning is particularly suited for flexible membranes [42]. The NPF was flexible, and could be easily peeled off, washed and regenerated (Fig. S3e, f).

Durability is important in practical solar desalination. The rGO/Au NPs nanoplates were used as control and 2% KI/I₂ solution was added in seawater to simulate the erosion during desalination. As shown in Fig. 5f, the average weight change was 2.66 kg m⁻² and showed negligible deviation from the initial weight change even after 30 cycles. For each cycle, the absorption layer was illuminated under 10 kW m⁻² for 15 min. Then, the nanoplates were washed and dried for the next cycle. In contrast, the weight change of the rGO/Au NPs dropped at the first several cycles and reached stable state afterwards (Fig. 5f). After the cycling test, the rGO/Au NPs turned into bare rGO due to the etching by KI/I₂ and the detachment of the particles during washing, while the morphology of the rGO/Au NPs/rGO nanoplates still

remained unchanged. In the water reservoir, Au³⁺ concentration of the rGO/Au NPs sample was 30.38 mg L⁻¹ while that of the rGO/Au NPs/rGO was 0.88 mg L⁻¹ after the solar desalination. Besides, another 30-cycles test of the same sample was conducted after aging treatment for one month under ambient condition, as shown in Fig. S5d, showing no further reduction. Moreover, NPs dipped in water directly would inevitably detach from the device. The sandwich-like rGO/Au NPs/rGO nanoplates was free of this concern. Because the Au NPs were packed in the interlayers of nanoplates, and the micrometer nanoplates could be easily separated from water by simple filtration, avoiding the secondary pollution.

CONCLUSIONS

In summary, we designed a kind of sandwich-like rGO/Au NPs/rGO nanoplates by using MS as the sacrificial template. The surface melting effect of MNPs was depressed and the thermal stability of Au NPs in the sandwich-like rGO/Au NPs/rGO nanoplates was enhanced. After being heated at 500°C, 60% confined Au NPs in the sandwich-like nanoplates could be preserved. Meanwhile, the unconfined Au NPs could be easily etched by KI/I₂ solution, while the Au NPs confined in the rGO/Au NPs/rGO were able to maintain the original state, showing good chemical stability. The sandwich-like rGO/Au NPs/rGO nanoplates were filtered on filter paper and applied as the light absorption layer for a solar evaporator. The device showed a high evaporation efficiency of 85.2% under a high solar flux of 10 kW m⁻² due to the enhanced photothermal effect of plasmonic Au NPs. In addition, the solar evaporator was used for seawater desalination. After a 30-cycles test, the solar evaporator showed good recycling performance and anticorrosion property. In a word, the method with commercial MS as the sacrificial template to prepare sandwich-like rGO nanoplates is quite efficient. Such sandwich-like rGO/Au NPs/rGO nanoplates with enhanced stability may have potential application in seawater desalination.

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Author contributions Yu SH supervised the project and wrote the paper; Zhu HW carried out the experiments, analyzed the results, and wrote the paper; Ge J, Zhao HY, and Xu L provided helpful discussion about the paper; Zhao HY analyzed the nanostructure and the mechanism of formation; Huang J performed the SEM measurements; Zhao HY, Shi LA, and Huang J assisted with the solar desalination experiments. All authors discussed the results and assisted during manuscript preparation.

Conflict of interest The authors declare that they have no conflict of interest.

Supplementary information Experimental details and supporting data are available in the online version of the paper.

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海绵模板法制备三明治结构的还原氧化石墨烯限域金纳米颗粒纳米片助力光热水蒸发

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摘要 基于等离子体金属纳米颗粒的光热水蒸发技术具有广阔的发展前景. 然而, 由于金属纳米颗粒的不稳定性, 高温下金属纳米颗粒将发生表面熔融, 水中的腐蚀性离子也能通过扩散作用直接与金属纳米颗粒结合而将其刻蚀. 因此, 长时间循环会使得金属纳米颗粒出现明显的性能衰减. 为了解决这些问题, 我们基于海绵模板法设计合成了一种具有三明治结构的夹心纳米片, 其中金纳米颗粒限域在还原氧化石墨烯纳米片的层间. 得益于限域效应, 表面熔融效应和离子扩散现象都得到了很好的抑制. 基于此夹心纳米片, 我们构建了一种光热水蒸发器. 在10 kW的高光强下, 该水蒸发器表现出高达85.2%的光-水蒸气转换效率, 经过30次循环海水淡化实验, 性能一直保持稳定, 没有出现明显衰减, 表明这种通过三明治结构限域金纳米颗粒的设计有利于促进光热海水淡化技术的实际应用.