Anisotropic vanadium dioxide sculptured thin films with superior thermochromic properties

Yaoming Sun¹, Xiudi Xiao¹, Gang Xu¹, Guoping Dong², Guanqi Chai¹, Hua Zhang¹, Pengyi Liu³, Hanmin Zhu² & Yongjun Zhan¹

¹Key Laboratory of Renewable Energy and Gas Hydrates, Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, Guangzhou, 510640 P. R. China, ²State Key Laboratory of Luminescent Materials and Devices, South China University of Technology, Guangzhou, 510640 P. R. China, ³Jinan University, Guangzhou, 510640 P. R. China.

VO₂ (M) STF through reduction of V₂O₅ STF was prepared. The results illustrate that V₂O₅ STF can be successfully obtained by oblique angle thermal evaporation technique. After annealing at 550°C/3 min, the V₂O₅ STF deposited at 85° can be easily transformed into VO₂ STF with slanted columnar structure and superior thermochromic properties. After deposition SiO₂ antireflective layer, Tlum of VO₂ STF is enhanced 26% and ΔTsol increases 60% compared with that of normal VO₂ thin films. Due to the anisotropic microstructure of VO₂ STF, angular selectivity transmission of VO₂ STF is observed and the solar modulation ability is further improved from 7.2% to 8.7% when light is along columnar direction. Moreover, the phase transition temperature of VO₂ STF can be depressed into 54.5°C without doping. Considering the oblique incidence of sunlight on windows, VO₂ STF is more beneficial for practical application as smart windows compared with normal homogenous VO₂ thin films.
Figure 1 | SEM surface and cross-sectional images of as-deposited V$_2$O$_5$ sculptured thin films deposited at different oblique angle. (a, c) 0°; (b, f) 85°; (d) 60°; (e) 80°. The scale bar in Fig. 1 (c) is 200 nm. The other scale bar is 500 nm.

Figure 2 | SEM images of V$_2$O$_5$ sculptured thin films deposited at 85° after annealing at different temperature for 5 min. (a) 500°C; (b) 550°C; (c) 600°C; (d) 700°C. The scale bar is 500 nm.

Figure 3 | XRD patterns of V$_2$O$_5$ sculptured thin films deposited at 85° after annealing at different temperature for 5 min.
The microstructure of STF can show angular selectivity transmission. Combination with VO₂ thin films and OAD technique, it is supposed that VO₂ STF can show superior luminous transmittance and solar modulation ability. In present paper, the optical properties and phase transition process of VO₂ STF were investigated. The results illustrated that VO₂ STF with slanted columnar structure can show superior thermochromic properties and angular selectivity transmission, which can be improved by antireflective layer design. The phase transition temperature of VO₂ STF can be depressed into 54.5°C without doping, which is superior to normal VO₂ film without doping. Due to the porosity, the refractive index of antireflective windows.

**Results**

**VO₂ sculptured thin films.** SEM images of as-deposited VO₂ STF deposited at different angles are shown in Fig. 1. It can be found that the thin films are porous with OAD technique (see Fig. 1(a, b)). With the increase of deposition angle, films are with slanted columnar structure. The columns incline towards the direction of the incoming flux. The higher the deposition angle is, the greater the column inclination is. The highly orientated nansotecture of the slanted columns indicates that VO₂ films are anisotropy, with the long axis parallel to the columnar growth direction. The anisotropic structure will introduce the anisotropic dependence into the thermal, electrical, magnetic and optical properties of thin films.

Column angle β, defined as the angle between substrate surface normal and the long axis of slanted columns, is a significant structural parameter. As can be seen, the column angle increases with the increase of deposition angle. There are two empirical formulæ developed to estimate column angle at oblique incidence: (1) tangent rule \((\tan \beta = 0.5 \tan \alpha, \alpha < 70°)\); (2) cosine rule \((\cos \alpha = 1 - \cos \beta = 0.5 \sin \alpha, \alpha > 70°)\). However, the experimental column angle measured from SEM images is about 25°, 42°, 47° for α = 60, 80, 85°, respectively, which are rather lower than the value estimated by the tangent rule \((\beta = 40.9° \text{ at } \alpha = 60°)\) and cosine rule \((\beta = 55.6° \text{ at } \alpha = 80°)\) and \(\beta = 57.8° \text{ at } \alpha = 85°\). The origin of the deviation may be due to the great surface curvature of nanostructure films grown by OAD. This will distinctly change the direction of column angle compared to that of micro-sized thin films. Additionally, the column angle also depends on the deposited material. Hodgkinson and Wu proposed the modified tangent rule \((\tan \beta = E_1 \tan \alpha)\) and the parameter \(E_1\) is variable with different materials. As to VO₂ STF, the relationship between β and α obeys exponential function fitted by the results of SEM measurements (see the insert of Fig. 1(a)).

The effect of annealing temperature. It is well-known that deposition angle is an important factor to sculpture films structure by OAD technique. However, in our experiment, VO₂ (M) STF is indirectly obtained through VO₂ STF. It can be deduced that annealing conditions can play a great effect on the microstructure of VO₂ (M).

To obtain VO₂ STF, VO₂ STF was reduced in hydrogen atmosphere. After annealing, the morphology and structure of STF were greatly changed just as shown in Fig. 2. According to the SEM images of VO₂ STF annealed at different temperature, it can be found that the columnar structure become aggregation. The gap between columns in the same row is decreasing after annealing at 500°C. When the annealing temperature is up to 550°C, the intact columnar structure can not be observed and conglutination appears between columns. When the annealing temperature reaches 600°C, distinct particles on columns are observed and the single column becomes thick. When annealing temperature is up to 700°C, no column and porosity is observed and only polygonal particles disperse on the film surface. It means the sculptured thin films are completely destroyed at 700°C.

The XRD patterns of VO₂ STF deposited at different angles are shown in Fig. 3. It can be found that as-deposited thin film is polycrystalline with apparent peaks in XRD pattern, which is different from other oxide STF by evaporation method. The peaks are ascribed to VO₂ (ICPDS 89-0611). After annealing at hydrogen atmosphere, peaks ascribed to VO₂ disappear and some peaks ascribed to VO₂ (B) (ICPDS 81-2392) are observed. With the increase of annealing temperature, the peaks of VO₂ (B) are firstly enhanced at 500°C and then disappear at 550°C. When annealing temperature is higher than 550°C, no peaks of VO₂ (B) is observed and peaks ascribed to VO₂ (M) (ICPDS 43-1051) appear. It is known that VO₂ (B) can be transformed into VO₂ (M) at high temperature. However, the transformation temperature is higher than that observed in VO₂ (B) powder at inert atmosphere. According to our previous results on VO₂ (B) prepared by hydrothermal method, lower crystallinity of VO₂ (B) needs low transformation temperature. In present paper, the higher transformation temperature of VO₂ (B) may be resulted from the different structure of thin film and

| Table I | \(T_{\text{lum}} \), \(\Delta T_{\text{lum}} \), \(T_{\text{sol}} \), \(\Delta T_{\text{sol}} \), \(T_{\text{2000}} \), \(\Delta T_{\text{2000}} \) of VO₂ STF deposited at 85° after annealing at different temperature |
|---------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
|         | \(30°C \) | \(100°C \) | \(\Delta T_{\text{lum}} \) | \(30°C \) | \(100°C \) | \(\Delta T_{\text{sol}} \) | \(30°C \) | \(100°C \) | \(\Delta T_{\text{2000}} \) |
| 400°C   | 57.3     | 59.1     | −1.8                        | 52     | 53.4     | −1.4                        | 63.1     | 62.3     | 0.8                        |
| 500°C   | 40.7     | 40.9     | −0.2                        | 50.6   | 34.3     | 6.3                         | 57.8     | 24.4     | 33.3                       |
| 550°C   | 39       | 41.1     | −2.1                        | 41.5   | 35.7     | 5.8                         | 61.0     | 26.2     | 34.8                       |
| 600°C   | 21.4     | 25.1     | −3.7                        | 25     | 24.8     | 0.2                         | 44.3     | 23.2     | 21.1                       |
| 700°C   | 24.7     | 25.2     | −0.5                        | 26.5   | 27.6     | −1.1                        | 35.7     | 34.5     | 1.2                        |
preparation process. With the increase of annealing temperature, the peaks ascribed to VO$_2$ (M) are enhanced. When V$_2$O$_5$ STF is annealed at 700°C, two peaks at 12.2° and 29.2° appear, which can be ascribed to NaV$_6$O$_{15}$ (JCPDS 77-0146). It is inferred that sodium is from the glass substrate and high temperature is beneficial for the diffusion of Na$^+$ ions, which finally result in the formation of NaV$_6$O$_{15}$.

Transmission spectra of V$_2$O$_5$ STF after annealing are shown in Fig. 4. It can be found that as-deposited V$_2$O$_5$ STF show high transmission. After annealing, the transmission is reduced and the UV cut-off edge shifts to longer wavelength, which is resulted from the transformation of V$_2$O$_5$ to VO$_2$. According to the high (H) and low (L) temperature transmission spectra of VO$_2$ STF, the MIT transition is clearly observed as a dramatic infrared-transmittance change with temperature. The change of transmittance value is compiled in Table I.

It can be found that STF annealing at 400°C shows high $T_{\text{Lum}}$ and weak $D_{\text{Tsol}}$. With the increase of annealing temperature, the $T_{\text{Lum}}$ is gradually decreasing while the $D_{\text{Tsol}}$ is firstly increasing and then decreasing. It is known that the VO$_2$ (B) with broad band gap can show relatively high visible transmittance and $T_{\text{Lum}}$ while it cannot produce reversible phase transition below 100°C. Thus, V$_2$O$_5$ STF annealing at 400°C mainly containing VO$_2$ (B) does not show apparent infrared-transmission change (see Fig. 2). The decreasing of $T_{\text{Lum}}$ and increasing of $D_{\text{Tsol}}$ is resulted from the increasing content of VO$_2$ (M). Theoretically, the improved crystallinity and content of VO$_2$ (M) can result in the increase of $D_{\text{Tsol}}$. However, the $D_{\text{Tsol}}$ is decreasing for V$_2$O$_5$ STF annealing at 600°C and 700°C. For V$_2$O$_5$ STF annealing at 600°C, the aggregation of columns augment the distance of columns and minify the columnar angle, which result in the decreasing of columnar density and effective content of VO$_2$ (M) in fixed light spot size of transmittance testing. Thus, the $D_{\text{Tsol}}$ is still decreasing for thin films with superior crystallinity. For STF annealed at 700°C, VO$_2$ (M) particles are much more dispersive and the existence of NaV$_6$O$_{15}$ reduces the content of VO$_2$ (M). Therefore, STF annealed at 700°C show weak $D_{\text{Tsol}}$. Conventionally, the transmission change at wavelength of 2000nm is another factor to evaluate the spectral modulation ability. According to the transmittance spectra, $\Delta T_{2000}$ is also shown in Table I. The change of $\Delta T_{2000}$ is consistent with the change of $D_{\text{Tsol}}$, which is further proved our above mentioned analysis. According to the optical properties and microstructure of thin films, it can be deduced that the optimum annealing temperature is about 550°C.

The effect of annealing time. SEM images of V$_2$O$_5$ STF after annealing at 550°C for different time are shown in Fig. 5. It can be found that short time heat treatment does no effect on the morphology of thin films, which are still porous with slanted columns. With the elongation of annealing time, the particles grow up and some columns begin aggregation. When annealing time is up to 5 min, some columns begin to melt and become coarse. The pores between columns are enlarging. When annealing time reaches 8 min, no columns can be observed. Only abnormal bulk-like structures with big pores are existent on the film surface, which means that the regular porous columnar structure is completely destroyed after long time heat treatment.

The XRD patterns of V$_2$O$_5$ STF annealing at 550°C for different time are shown in Fig. 6. It can be found that only several weak peaks appear in the XRD pattern of V$_2$O$_5$ STF annealing for 1 min, which are ascribed to VO$_2$ (B). When the annealing time reaches 3 min, thin films completely transform into VO$_2$ (M).

The transmission spectra of V$_2$O$_5$ STF annealing at 550°C for different time are shown in Fig. 7. It can be found that the transmission is decreasing with the increase of annealing time and the UV...
The effect of deposition angle. The morphology of V$_2$O$_5$ STF deposited at different oblique angles after annealing at 550 °C/3 min are shown in Fig. 8. It can be found that the morphology was greatly changed after annealing. For V$_2$O$_5$ thin films deposited at 0°, the film is compact (see Fig. 1). After annealing, the films become porous with abnormal structure on the surface. While for V$_2$O$_5$ thin films deposited at 60°, the columnar structure is completely destroyed after annealing and only some belt like particles are existent on the surface. For V$_2$O$_5$ thin films deposited at 85°, the surface is like melted after annealing and the columns aggregates which make the column more inclined with higher column angle. The column angle is about 60°, but the arrangement of columns is not regular compared with as-deposited V$_2$O$_5$ STF at 80°. For V$_2$O$_5$ thin films deposited at 85°, the morphology and column structure is almost constant after annealing except for the increased column angle. It is known that large column angle can result in large anisotropy and high porosity, which can resulted in low refractive index and high visible transmission.

Transmittance spectra of V$_2$O$_5$ STF deposited at different oblique angles after annealing at 550 °C/3 min are shown in Fig. 9. It can be found that the transmittance is remarkably enhancing with the increase of deposition angle. It is proposed that the increase of deposition angle can increase the porosity in films and reduce the refractive index of films, which can result in the increase of transmission. For film deposited at 85°, the ultraviolet cut-off edge of VO$_2$ (M) STF is even smaller than 400 nm, which means that optical band gap is increased and the refractive index is sharply reduced by deposition angle adjustment. The optical properties of $T_{\text{lum}}$ and $\Delta T_{\text{sol}}$ are compiled in Table III.

Discussion
It can be found that $T_{\text{lum}}$ is increasing with deposition angle while the variation of $\Delta T_{\text{sol}}$ is not consistent with $T_{\text{lum}}$ in Table III. Generally, the visible transmittance at 30° is lower than that at 100° (see Table I and II). However, the visible transmittance at 30° of 0° deposited film exceed that at 100° (see Table III). Xu et al. and Kang et al. proposed that film thickness dependent interference effects can result in the reversion of $\Delta T_{\text{lum}}$. In view of the fact that solar energy is mainly in the visible region with a peak at 550 nm, the $\Delta T_{\text{lum}}$ reversion across the MIT greatly influences $\Delta T_{\text{sol}}$. Thus, film deposited at 0° shows larger $\Delta T_{\text{sol}}$ than that of films deposited at other deposition angle. However, the absolute value of $\Delta T_{\text{lum}}$ is related with both $\Delta T_{\text{lum}}$ and infrared modulation ($\Delta T_{2000}$). The variation of $\Delta T_{2000}$ is resulted from the crystallinity, content and film structure of VO$_2$ (M). The increase of deposition angle can result in the high porosity and relative low content of VO$_2$ (M) as well as low infrared modulation. Thus, films deposited at 85° show high visible transmittance and relative low solar ability.

| Table II | $T_{\text{lum}}$, $\Delta T_{\text{lum}}$, $T_{\text{sol}}$, $\Delta T_{\text{sol}}$, $T_{2000}$, $\Delta T_{2000}$ of V$_2$O$_5$ STF deposited at 85° after annealing at 550 °C for different time |
|----------------|-------------------------------------|----------------|----------------|----------------|----------------|
| $T_{\text{lum}}$ [%] | $\Delta T_{\text{lum}}$ | $T_{\text{sol}}$ [%] | $\Delta T_{\text{sol}}$ | $T_{2000}$ [%] | $\Delta T_{2000}$ |
| 30 °C | 100 °C | 30 °C | 100 °C | 30 °C | 100 °C | 30 °C | 100 °C | 30 °C | 100 °C |
| 1 min | 16.8 | 16.9 | -0.1 | 59 | 58.6 | 0.4 | 72.6 | 70.4 | 2.2 |
| 3 min | 40 | 42.1 | -2.1 | 42.8 | 43.2 | 5.6 | 66.2 | 30.6 | 35.6 |
| 5 min | 39 | 41.1 | -2.1 | 41.5 | 35.7 | 5.8 | 61.0 | 26.2 | 34.8 |
| 8 min | 28.7 | 32.1 | -3.4 | 38.4 | 31.9 | 6.5 | 68.5 | 24.4 | 44.1 |

Figure 8 | SEM surface and cross-sectional images of V$_2$O$_5$ sculptured thin films deposited at different oblique angles after annealing at 550° C/3 min. (a, e) 0°; (b, f) 60°; (c, g) 80°; (d, h) 85°. The scale bar is 200 nm.
To determine the phase-transition temperature of the VO2 STF, hysteresis loops of pure and tungsten-doped VO2 STF were measured by recording transmittances and temperatures of STF at a fixed optical wavelength (2000 nm). As seen in Fig. 10, pure VO2 film shows hysteresis loop width of 6°C at mean transmittance, which is consistent with that of pure VO2 film on glass. The mean phase transition temperature (Tt) is about 54.5°C, which is much lower than that of pure VO2 films (68°C) deposited by other methods. It is known that phase transition temperature can be depressed by doping, finite size and inhomogeneous strain. For VO2 STF without doping, films are porous with tilted columnar structure and the residual stress is huge. It can be deduced that the depressed phase transition temperature may be resulted from inhomogeneous strain in film. After tungsten doping, VO2 films exhibited a hysteresis loop centered at 35.8°C with a width of 9.7°C, implying a decrease in the phase transition temperature of about 17.7°C. This decreasing efficiency is less than that described in other reports, likely because the tungsten ions were not completely incorporated into the final VO2 films. The width widening of the hysteresis loop can be attributed to the states of grain boundaries and defects introduced by tungsten doping. It is known that tungsten doping can result in both the widening of the hysteresis loop and the difference in states of grain boundaries and defects introduced by tungsten doping.

Deposition antireflective layer is an important factor to improve luminous transmittance. Generally, antireflective layer with refractive index about 2 — 2.5 is proposed as the superior material for common VO2 film. Considering VO2 STF deposited by OAD technique with gradient refractive index, refractive index of antireflective layer can be lower than 2. Though the real refractive index of VO2 STF was not tested due to the limit of instrument, silicon dioxide with refractive index about 1.46 (n = 550 nm) was used as antireflective layer to prove our supposition. The transmission spectra of V2O5 STF deposited at 0° and 85° after annealing at 550°C/3 min before and after SiO2 antireflective layer deposition are shown in Fig. 11. It can be found that the transmission spectra are greatly changed after antireflective layer deposition with the same thickness. For films deposited at 0°, besides the increase of transmission, the position of interference peaks was not changed after SiO2 layer deposition. While for films deposited at 85°, the position of interference peak shifts to shorter wavelength accompanying with the enhanced transmittance. The reason may be that relatively smaller equivalent thickness and the low refractive index of VO2 films deposited at 85° show strong interferences with SiO2 antireflective layer, which results in the blue shift of interference peaks. The Tlum and ΔTsol are compiled in Table IV. After SiO2 deposition, Tlum of VO2 film deposited at 0° increases 20% (32.7% to 39.5%) and ΔTsol increases 15% (6.6% to 7.6%), while Tlum of VO2 film deposited at 85° is enhanced 26% (36.9% to 46.6%) and ΔTsol increases of 60% (4.5% to 7.2%), which means that SiO2 antireflective layer is much more effective to improve luminous transmission and solar modulation ability of VO2 STF than normal VO2 films.

It is known that VO2 STF with slanted columnar structure can show anisotropy optical properties. The transmission of STF along and perpendicular to column direction is obviously different. For convenience to prove, transmission spectra of 0° and ±30° incidence are shown in Fig. 12. Tlum and ΔTsol according to transmission spectra are compiled in Table V. For VO2 deposited at 0°, Tlum and ΔTsol of +30° light incidence are almost the same with that of −30° light incidence, but it is much smaller than that of 0° incidence. For the homogeneous film, transmission of light oblique incidence is smaller than that of normal incidence according to interference optics. However, the result is absolutely different for anisotropic VO2 STF. For VO2 deposited at 85°, Tlum of +30° light incidence is smaller than that of −30° and 0° light incidence, but ΔTsol is higher than that of −30° and 0° incidence. This reason may be that +30° light incidence is along columnar direction and the effective thickness of VO2 (M) is larger than that of −30° and 0° light incidence. Thus, Tlum is relatively smaller than that of −30° and 0° light incidence and ΔTsol is higher than that of −30° and 0° light incidence. For VO2 deposited at 85° with SiO2 antireflective layer, ΔTsol of +30° light incidence is enhanced 20% with only 4% decrease of Tlum compared with normal incidence. Factually, sunlight is oblique incidence onto windows, the angle selective transmission of VO2 STF is more beneficial for practical application.

Considering the polarization effect and anisotropy of STF films, the polarization transmittance spectra are shown in Fig. 13. For VO2 films deposited at 0°, films are homogeneous. There is no polarization effect observed when polarization light is 0° incidence just as see in Fig. 13 (a). While the transmission spectra of P-light and S-light are divided and polarization effect happens when incidence angel is 30°. For VO2 deposited at 85°, films are anisotropy with slanted columns. The P and S lights are separated and the transmission spectra cannot be overlapped when polarization incidence is 0° (see Fig. 13 (d)), which means the optical anisotropy is observed in VO2 STF and is consistent with the results in other oxides films. When incident light is oblique, the polarization effect is amplified just as in
Simultaneously, the polarization effect is more distinct when light is along the direction of columns. For VO$_2$ deposited at 85$^\circ$C with a layer of SiO$_2$, the structure of films is changed and the anisotropy is reduced. Thus, the polarization effect and optical anisotropy is not apparent (see Fig. 13 (i, g, h)). Due to phase transition of VO$_2$ films at high and low temperature, the polarization effects need further study in future.

In conclusion, V$_2$O$_5$ STF with slanted column structure was prepared by oblique angle thermal evaporation technique. After annealing, V$_2$O$_5$ STF can be transformed into VO$_2$ STF with the melting and aggregation of columnar structure. VO$_2$ STF with slanted columnar structure can be obtained at 550$^\circ$C/3 min for V$_2$O$_5$ STF deposited at 85$^\circ$. Due to the porous structure and low refractive index, SiO$_2$ can be used as effective antireflective layer to improve luminous transmittance and solar modulation ability. After SiO$_2$ deposition, $T_{\text{lum}}$ of VO$_2$ films deposited at 85$^\circ$ is enhanced 26% (36.9% to 46.6%) and $\Delta T_{\text{sol}}$ increases 60% (4.5% to 7.2%). Due to the anisotropic column structure, angle selective transmittance is observed for VO$_2$ (M) STF. The solar modulation ability is further improved for light along the columnar direction especially for VO$_2$ (M) STF with SiO$_2$ antireflective layer (7.2% to 8.7%). Moreover, the phase transition temperature of VO$_2$ STF is greatly depressed into 54.5$^\circ$C without doping. Considering the oblique incidence of sunlight on windows, VO$_2$ (M) STF is more suitable as smart window compared with normal homogeneous VO$_2$ (M) films.

| $T_{\text{lum}}$ [%] | $\Delta T_{\text{lum}}$ | $T_{\text{sol}}$ [%] | $\Delta T_{\text{sol}}$ | $T_{2000}$ [%] | $\Delta T_{2000}$ |
|---------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| 0$^\circ$ VO$_2$ | 32.7 | 33.1 | -0.4 | 35.2 | 28.6 | 6.6 | 59.1 | 15.9 | 43.2 |
| 0$^\circ$ VO$_2$ + SiO$_2$ | 39.5 | 39.5 | 0 | 39.3 | 31.7 | 7.6 | 56.4 | 15.8 | 40.6 |
| 85$^\circ$ VO$_2$ | 36.9 | 38.6 | -1.7 | 39.7 | 35.2 | 4.5 | 63.9 | 21.5 | 42.4 |
| 85$^\circ$ VO$_2$ + SiO$_2$ | 46.6 | 45.3 | 1.3 | 45.1 | 37.9 | 7.2 | 68.9 | 27.3 | 41.6 |
Figure 12 | Transmittance spectra of V₂O₅ STF deposited at 0° and 85° after annealing at 550 °C/3 min with testing light incidence angle of 0° and ±30°. (a) VO₂ deposited at 0°; (b) VO₂ deposited at 85°; (c) VO₂ deposited at 85° with a layer of SiO₂.

Table V | Tₜₐₜ, ΔTₜₐₜ, Tᵣᵣᵣᵣ, ΔTᵣᵣᵣᵣ, T₂₀₀₀₀, ΔT₂₀₀₀₀ of V₂O₅ STF deposited at 0° and 85° after annealing at 550 °C/3 min with 0° and ±30° incidence testing

| Deposition angle (α) | Testing angle (θ) | Tₜₐₜ [%] | ΔTₜₐₜ | Tᵣᵣᵣᵣ [%] | ΔTᵣᵣᵣᵣ |
|----------------------|------------------|----------|-------|------------|---------|
| 0°                   | 0°               | 24.7     | -2.7  | 31.3       | 6.9     |
|                      | +30°             | 22.1     | -5.2  | 30.0       | 4.1     |
| 85°                  | 0°               | 25.1     | -2.9  | 27.7       | 4.4     |
|                      | +30°             | 33.9     | 0.3   | 34.8       | 6.4     |
|                      | -30°             | 34.5     | 0.2   | 33.3       | 7.0     |
| 85° + SiO₂           | 0°               | 32.2     | 0.3   | 35.1       | 6.1     |
|                      | +30°             | 46.6     | 1.3   | 45.1       | 7.2     |
|                      | -30°             | 42.8     | 1.3   | 44.7       | 8.7     |

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Methods
Preparation. V2O5 sculptured thin films were deposited by thermal evaporation at base pressure of 5 × 10^{-7} Pa with OAD technique. BK7 glass was ultrasonically cleaned in acetone and ethanol before introducing into the vacuum system. V2O5 powder (purity: 99.5%) were evaporated from a tungsten boat located 20 cm from the substrate. The deposition equipment was similar to our previous work18. The substrate tilted angle was fixed to be 0°, 60°, 80°, 85° without substrate rotation. During deposition, substrate was kept at room temperature. After deposition, V2O5 STF was annealed in an infrared lamp heating system (Mila-5000, ULVAC) with heating rate about 50°C/s in hydrogen atmosphere. For antireflective layer deposition, SiO2 sol was spinning on the surface of V2O5 films at speed of 2000 rpm.

Characterization. The X-ray diffraction (XRD) patterns were obtained on X’Pert Pro MPD diffractometer, using Cu Kα radiation at a scan rate of 0.02° S^{-1}. A Hitachi S-4800 scanning electron microscope (SEM) equipped with energy dispersive spectrum (EDS, HORIBA EX-250) was used to acquire SEM images. The thermochromic property was monitored on a PerkinElmer Lambda 750 spectrophotometer equipped with a film heating unit in the wavelength range of 300–2500 nm. Temperature was measured by a temperature sensor in contact with the substrate tilted angle. In our experiment, the deposition angle was fixed to be 0°, 80°, 85° with a layer of SiO2.

Figure 13 | Polarization transmittance spectra of V2O5 STF deposited at 0° and 85° after annealing at 550°C/3 min with testing light incidence angle of 0° and ±30°. (a, b, c) VO2 deposited at 0°; (d, e, f) VO2 deposited at 85°; (i, g, h) VO2 deposited at 85° with a layer of SiO2.

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Author contributions
X.D.X. proposed and guided the overall project. Y.M.S., G.X., G.P.D., G.Q.C., H.Z., P.Y.L., H.M.Z. and Y.J.Z. performed all the experiments and analyzed the results. All the authors discussed the results. X.D.X. and Y.M.S. wrote the manuscript, with discussion from G.X.

Additional information
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