Supplementary Information (SI) for Nanoscale.
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Supplemental Information:

Fig. S1 TEM image and corresponding EDS elemental mapping image of WO_3.

Fig. S2 TEM image of WO_3-HAC with HRTEM image of the corresponding dashed box regions.

Fig. S3 EDS of W, O and C in (a) WO_3 films and (b) WO_3-HAC films.

Fig. S4 PDOS patterns of O 2p and W 5d orbitals for WO_3-HAC.

Fig. S5 I-T curves of WO_3, WO_3-HAC and WO_3-CA films.

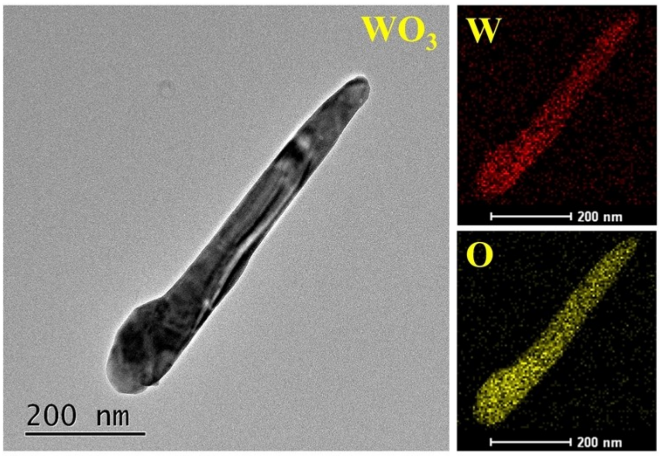
Fig. S6 CV curves for (a) WO_3, (b) WO_3-HAC and (c) WO_3-CA in the region of OCP±50 mV (V vs. Ag/AgCl) with various scan rates. CV curves for (d) WO_3, (e) WO_3-HAC and (f) WO_3-CA with various scan rates.

Tab. S1 EDS elemental mapping of O, W, C and Ce in WO_3, WO_3-HAC and WO_3-CA films.

Tab. S2 Percentage XPS atoms of W, C, Ce and O in WO_3, WO_3-HAC and WO_3-CA films.

Tab. S3 Impedance fitting circuit diagrams for WO_3, WO_3-HAC, and WO_3-CA samples.

Tab. S4 Comparison of transmittance change, coloring time, and bleaching time for various WO_3-based electrochromic materials.



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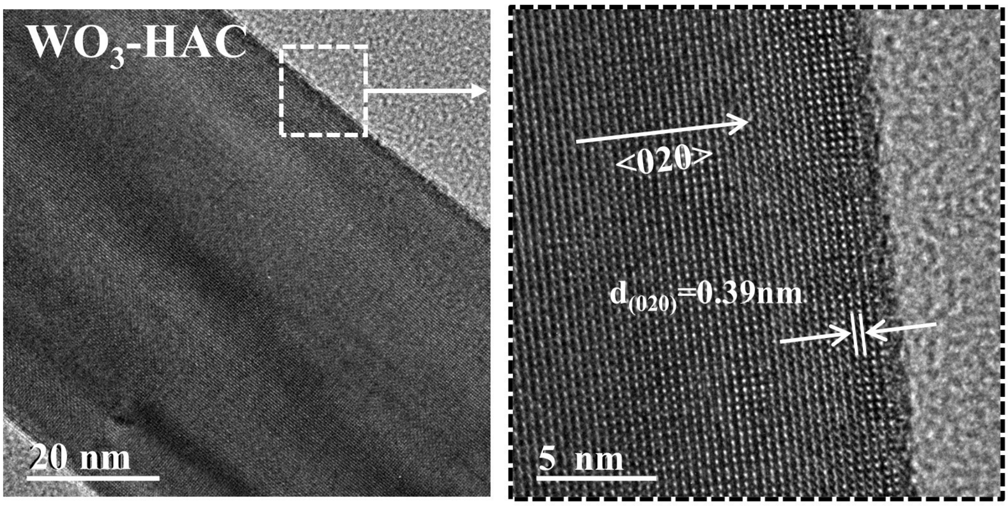

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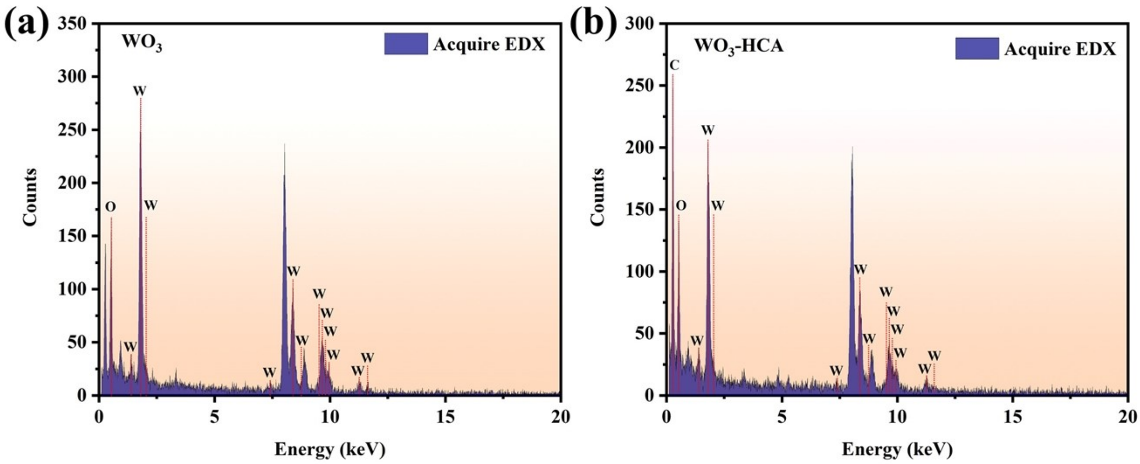

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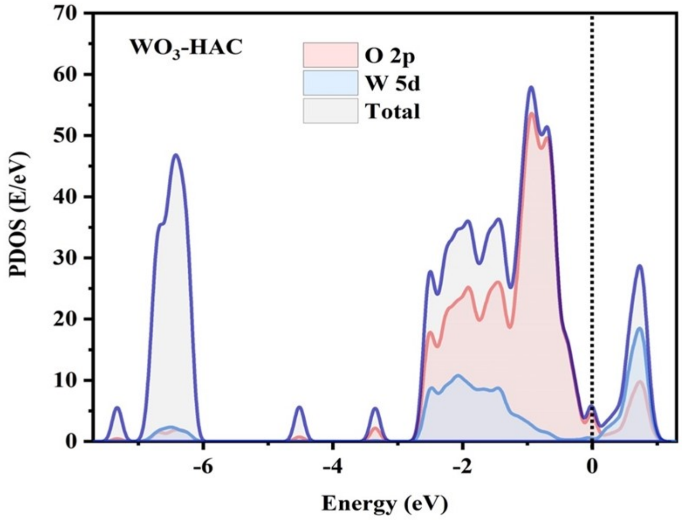

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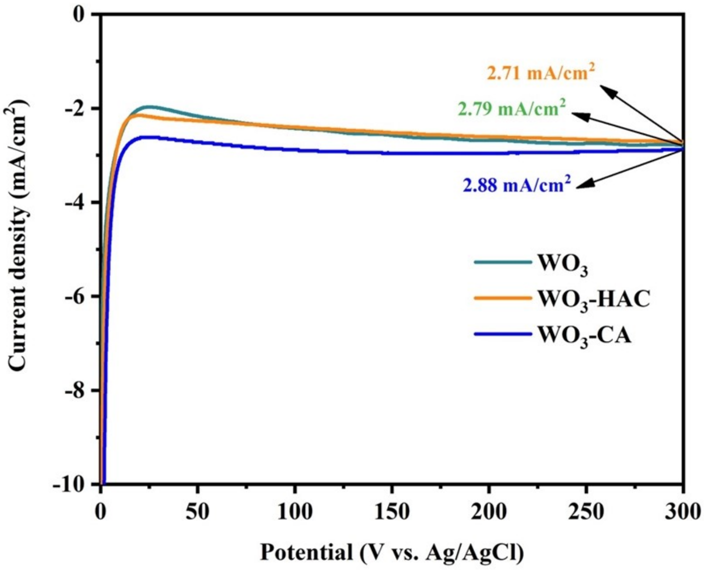

Fig. S5 I-T curves of WO_3, WO_3-HAC and WO_3-CA films.

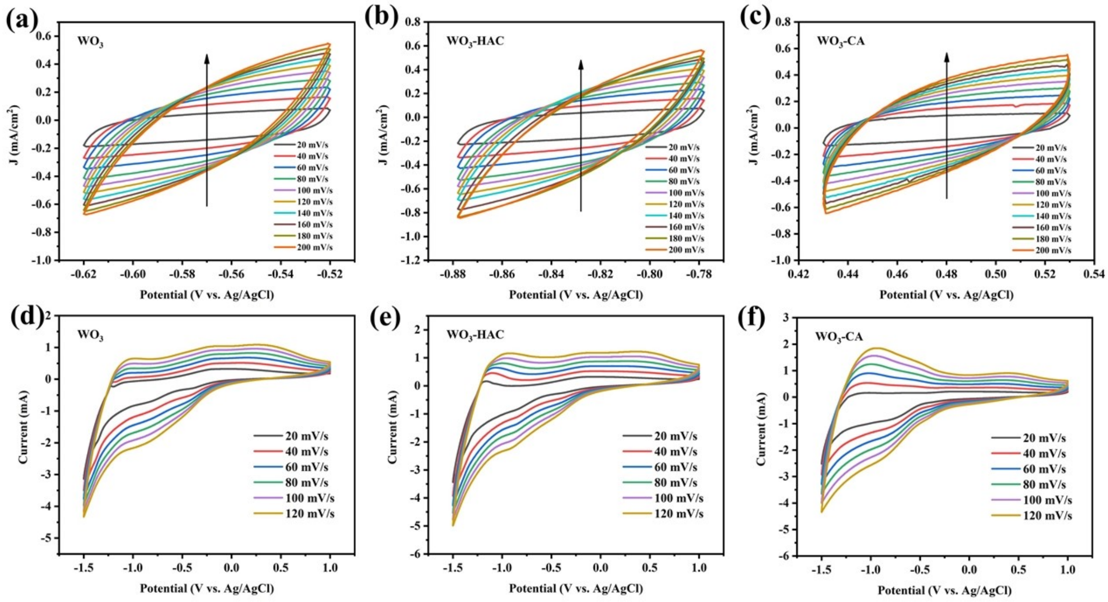

Fig. S6 CV curves for (a) WO_3, (b) WO_3-HAC and (c) WO_3-CA in the region of OCP±50 mV (V vs. Ag/AgCl) with various scan rates. CV curves for (d) WO_3, (e) WO_3-HAC and (f) WO_3-CA with various scan rates.

Tab. S1 EDS elemental mapping of O, W, C and Ce in WO_3, WO_3-HAC and WO_3-CA films.

Element	WO_3	WO_3-HAC	WO_3-CA
O(K)	78.82	17.45	13.57
W(L)	21.18	4.45	6.15
C(K)	-	78.10	80.07
Ce(K)	-	-	0.21
Total	100.00	100.00	100.00

Tab. S2 Percentage XPS atoms of W, C, Ce and O in WO_3, WO_3-HAC and WO_3-CA films.

Name	WO_3	WO_3-HAC	WO_3-CA
W 4f	14.97	14.83	10.14
C 1s	15.9	35.53	40.95
Ce 3p	-	-	0.5
O 1s	69.13	49.64	48.41

Tab. S3 Impedance fitting circuit diagrams for WO_3, WO_3-HAC, and WO_3-CA samples.

Samples	R_1	R_2	W_1R	W_1T	W_1P	CPE_1T	CPE_1P
WO_3-CA	9.33	33.21	431.1	0.425	0.758	0.469	0.742
WO_3-HAC	38.72	52.33	711.3	0.722	0.739	1.352	0.793
WO_3	61.38	52.45	864.7	0.755	0.747	0.528	0.833

Tab. S4 Comparison of transmittance change, coloring time, and bleaching time for various WO_3-based electrochromic materials.

Sample	Transmittance Difference (%)	Coloring Time (s)	Bleaching Time (s)	Reference
WO_3	31.6 (600 nm)	3.1	3.1	This Work
WO_3-HAC	34.5 (600 nm)	2.6	2.6	This Work
WO_3-CA	52.0 (600 nm)	2.1	2.1	This Work
WO_3/V_2O_5	57.0 (776 nm)	4.8	4.4	[1]
CdSe QDs-WO_3	54.5 (700 nm)	13.3	11.5	[2]
Gd-doped WO_3	~60 (633 nm)	10.4	7.8	[3]
WO_3 $0.33H_2O$/PEDOT	50.9 (633 nm)	5	25	[4]
WO_3/MoO_x	55.4 (650 nm)	3.6	7.4	[5]
WO_3-Sm	73.8 (633 nm)	9.6	3.8	[6]
WO_x nanorods	57.0 (600 nm)	11.8	20.1	[7]

1.Materials section

The main reagents used in this experiment include lithium perchlorate ($LiClO_4$, analytically pure, Tianjin Jiangtian Unified Technology Co., Ltd.), potassium oxalate ($K_2C_2O_4 \cdot H_2O$, analytically pure, Tianjin Kewei Co., Ltd.), sodium tungstate dihydrate ($Na_2WO_4 \cdot 2H_2O$, analytically pure, Shanghai Macklin Biochemical Technology Co., Ltd.), polycarbonate (PC, analytically pure, Shanghai Macklin Biochemical Technology Co., Ltd.), nickel chloride hexahydrate ($NiCl_2 \cdot 6H_2O$, analytically pure, Shanghai Eon Chemical Technology Co., Ltd.), hydrochloric acid (HCl, analytically pure, Tianjin Damo Chemical Reagent Factory), and cerium acetate (analytically pure, Shanghai Macklin Biochemical Technology Co., Ltd.), acetic acid (analytically pure, Shanghai Macklin Biochemical Technology Co., Ltd.). All reagents are analytical grade and do not require further purification.

2.Charge density calculation

The charge density calculation can be seen in Eq:

$$Q = S/(VA) \tag{2}$$

Where Q represents the charge density (C/cm^2), S is the area enclosed by the cyclic voltammogram curve, V is the scan rate (V/s), and A is the surface area of the working electrode (cm^2) .

3.Peak current value calculation

The peak current value (i_p) can be calculated using the equation:

$$i_p = 2.69\times10^5 n^{3/2} A D^{1/2} C V^{1/2} \tag{3}$$

Where i_p represents the peak current value, n is the number of electrons involved in the electrochemical reaction (assumed to be 1), A is the electrode area of the film, D is the Li^+ diffusion coefficient, C is the ion concentration of Li^+, and V is the scan rate.

4.Calculation of transmittance difference

The calculation formula is as follows:

$$\Delta T = (T_b - T_c) \tag{4}$$

Where T_b and T_c represent the transmittance of the sample under bleached and colored conditions, respectively, at a certain wavelength.

5.CE calculation

To further determine the coloring efficiency of the prepared samples, the following formula can be utilized:

$$CE = \Delta OD/Q_i \tag{5}$$

$$\Delta OD = \log (T_b/T_c) \tag{6}$$

Where CE represents the coloration efficiency (cm^2/C); ΔOD indicates the maximum change in optical density; Q_i is the quantity of charge injected or extracted per unit area. T_b and T_c are the transmittances in the bleached and colored states, respectively.

Reference:

[1] Tang K, Zhang Y, Shi Y, et al. Preparation of V_2O_5 dot-decorated WO_3 nanorod arrays for high performance multi-color electrochromic devices. Journal of Materials Chemistry C, 2018, 6: 12206-12216.

[2] Hasani A, Le Q V, Tekalgne M, et al. Tungsten trioxide doped with CdSe quantum dots for smart windows. ACS applied materials & interfaces, 2018, 10: 43785-43791.

[3] Yin Y, Lan C, Hu S, et al. Effect of Gd-doping on electrochromic properties of sputter deposited WO_3 films. Journal of Alloys and Compounds, 2018, 739: 623-631.
[4] Yue Y, Li H, Li K, et al. High-performance complementary electrochromic device based on $WO_3 \cdot 0.33H_2O$/PEDOT and prussian blue electrodes. Journal of Physics and Chemistry of Solids, 2017, 110: 284-289.
[5] Hsu S C, Chao S H, Wu N J, et al. Facile synthesis of hybrid WO_3/MoO_x electrochromic films for application in complementary electrochromic devices. Journal of Alloys and Compounds, 2023, 945: 169256.
[6] Luo G, Shen L, Zheng J, et al. A europium ion doped WO_3 film with the bi-functionality of enhanced electrochromic switching and tunable red emission. Journal of Materials Chemistry C, 2017, 5: 3488-3494.
[7] Chang X, Sun S, Dong L, et al. Tungsten oxide nanowires grown on graphene oxide sheets as high-performance electrochromic material. Electrochimica Acta, 2014, 129: 40-46.