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Letter

Toward the Prediction of Electrochromic Properties of WO_3 Films: Combination of Experimental and Machine Learning Approaches

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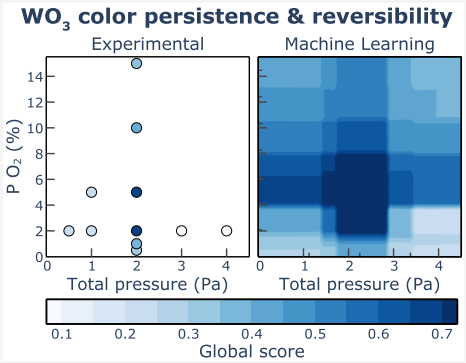
ABSTRACT: WO_3 is the state of the art of electrochromic oxide materials finding technological application in smart windows. In this work, a set of WO_3 thin films were deposited by magnetron sputtering by varying total pressure, oxygen partial pressure, and power. On each film two properties were measured, the electrochemical reversibility and the blue color persistence of Li_xWO_3 films in simulated ambient conditions. With the help of machine learning, prediction maps for such electrochromic properties, namely, color persistence and reversibility, were designed. High-performance WO_3 films were targeted by a global score which is the product of these two properties. The combined approach of experimental measurements and machine learning led to a complete picture of electrochromic properties depending of sputtering parameters providing an efficient tool in regards to time saving.



Global warming and increasing energy demand and consumption urge the search for novel approaches for energy saving. A large part of energy consumption in buildings comes from heating and air conditioning. In order to preserve a comfortable environment while saving energy, smart windows are a promising solution. Indeed, they allow the control of incident light radiation in a room while offering outdoor views.[1,2] Smart window technology is often based on electrochromic devices. Electrochromism is the ability of a material to change its optical properties under the appliance of a voltage.[3,4] Among electrochromic materials are found organic molecules, polymers, and metal oxides.[5] From this last category, WO_3 has been the most studied since the pioneering work of Deb.[6] When elaborated in the form of a thin film, WO_3 switches from a colorless state to a dark blue state with the insertion of small cations M (H^+, Li, and Na^+) according to $WO_3 + xe^- + xM^+ \Leftrightarrow M_xWO_3$. Electrochromic tungsten oxide films can be amorphous or crystallized depending on the temperature during the elaboration process.[7−9] WO_3 is known to present a self-bleaching behavior under its reduced state, leading to an increase of the transmittance in open-circuit conditions after the coloration.[10,11] Some authors reported that an additional layer of Ta_2O_5 on top of the WO_3 layer can contribute to increasing the persistence of the colored state of films or film-based devices once the applied voltage is withdrawn.[12,13] This property is called the memory effect which is defined by the persistence of the colored (or bleached) state for cathodic (anodic) electrochromic materials under open circuit conditions.[14] Thereby, the applied voltage to obtain the desired state does not need to be applied continuously which leads to an increase in energy saving of the device. Shi et al. showed that, depending on the sputtering conditions leading to different degrees of crystallinity, WO_3 films present a memory effect in air or in an electrolyte media.[15]

Generally, aiming to design materials with a desired set of characteristics, experimental research takes a long time to map different process conditions and to characterize them. Moreover, a limited number of samples can be prepared regarding the time and resources that it takes. In this context of designing properties of materials, machine learning can be a useful tool to help experimentalists.[16−18] This strategy has already been used for the discovery of new compounds in material science[19,20] and in the prediction of material properties[21,22] while having been scarcely explored in the field of electrochromic materials.[23] The aim of this study is to demonstrate that the traditional experimental approach can be nicely complemented by the use of machine learning algorithms to help find sputtering conditions leading to the desired electrochromic properties: color persistence (i.e., retention of color while no potential is applied) as well as good reversibility. Such a combination allows for a significant decrease of the experimental research duration.

WO_3 thin films were elaborated on an indium−tin oxide (ITO) substrate (commercialized by Solems with a resistance of 30 Ω/□) by radio frequency magnetron sputtering at

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different conditions by varying RF power, total pressure, oxygen partial pressure, and deposition time while keeping a similar film thickness in the range 210 nm ± 30 nm. Prior to the deposition process, the base pressure in the chamber was set below 3.10^{-5} Pa. Aiming at tuning the memory effect property and in order to map experimental conditions leading to the desired electrochromic properties, a set of WO_3 thin films was prepared by varying sputtering conditions using a WO_3 target of 75 mm in diameter and 3 mm thick (commercialized by Neyco). High reproducibility required a reoxidation of the target after each deposition performed at 75 W, 5 Pa, and 10% O_2 for 1 h. The initial deposition conditions were a power of 75 W, an oxygen partial pressure of 2% O_2, and a total pressure of 2 Pa. Figure 1 shows the cyclic

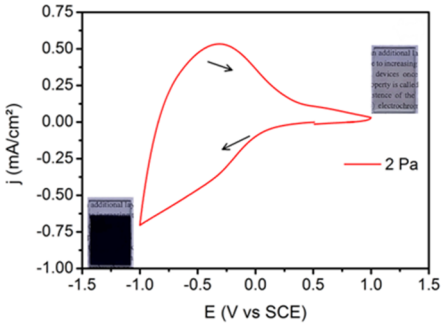

Figure 1. Cyclic voltammogram (first cycle) of WO_3/LiTFSI in EMIMTFSI (1:9 mol %)/Pt vs SCE cells recorded at 20 mV s^{-1}.

voltammogram of the WO_3 film cycled in a three-electrode cell in a lithium-based electrolyte. The CV shape is rather typical of amorphous WO_3 with a visual switch from colorless to dark blue color due to the electrochemical reduction of W^{6+} to W^{5+}.

The lithium insertion in WO_3 follows the equation

$$WO_3 + xe^- + xLi^+ \Leftrightarrow Li_xWO_3 \quad (1)$$

with an amount of inserted lithium of about 0.5 estimated during coloration by the equation $x = \frac{QM}{Fpt}$ where Q (C/cm^2) is the capacity in reduction calculated from $\frac{\int_{-1}^{1} j\,dV}{s}$, s is the scan rate (20 mV s^{-1}), M is the molar mass of WO_3 (231.84 g mol^{-1}), F is the Faraday constant (96 485 C mol^{-1}), p is the density estimated to be 75% of the theoretical WO_3 density (0.75 × 7.16 g/cm^3), and t is the film thickness.

The further cycling protocol consists of 5 CVs between −1 and +1 V followed by 5 chronoamperograms, CAs, at +1 and −1 V for 120 s, ending in the blue reduced state. Then, an *ex situ* optical measurement was performed on lithiated films just after coloration. In order to evaluate the memory effect of these films, transmission measurements were again recorded after 48 h in a climatic chamber at 25 °C ± 1.3 °C and 50 ± 2.5% relative humidity (R.H.). The optical transmittances of $Li_{0.5}WO_3$ films colored at −1 V for 120 s and after 48 h in the climatic chamber are shown in Figure 2. In an air-simulated controlled environment, the increase of the transmittance at 550 nm is only by 15.8% for the WO_3 film deposited at 2 Pa. After 48 h, the blue coloration persists indicating that the film presents a memory effect that lasts at least for 2 days.

The mapping was performed by keeping two parameters constant among power, 50 or 75 W, oxygen partial pressure in the range 0.5−15%, or total pressure in the range 0.5−4 Pa,

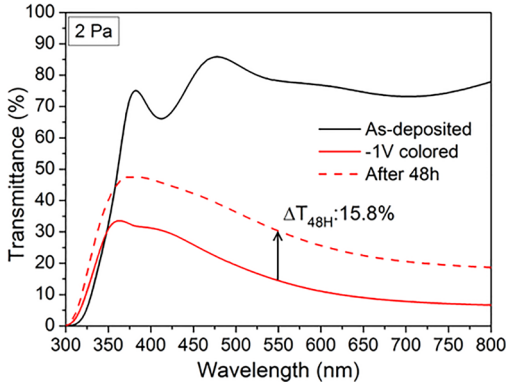

Figure 2. Optical transmittance of $Li_{0.5}WO_3$ before and after 48 h at 25 °C and 50% R.H.

and varying one parameter at the same time. Table 1 gathers the various sets of parameters and corresponding percentages of transmittance modulation, ΔT_{48h} on 12 samples.

In order to quantify the persistence of the blue color, i.e., the quality of the memory effect, a score using the following somewhat arbitrary formula was adopted:

$$\text{persistence score} = 1 - \frac{\Delta T_{48h}}{\Delta T_{48h}^{max}} \quad (2)$$

where ΔT_{48h} represents the difference in transmittance at 550 nm between as-colored films and after 48 h. ΔT_{48h}^{max} is the maximum value of ΔT_{48h} for the set of films. The formula gives a score between 0 and 1, where 0 is the lowest persistence, and 1 corresponds to the case where the transmittance at 550 nm is not evolving in 48 h. Based on the data collected for the 12 samples, a machine learning (ML) model was developed for the persistence score as a function of the deposition conditions. The ML model was based on the Random Forest algorithm, and the training procedure was repeated 20 times in a bootstrapping approach. The final prediction was taken as the average of the 20 predicted results, and their standard deviation provided a measure of the uncertainty. The MAE and RMSE on the persistence score were both smaller than 10%, with a coefficient of determination R^2 of 0.91 (Supporting Information).

Using the ML model, prediction maps for the color persistence of WO_3 were designed as a function of the sputtering conditions (oxygen partial pressure and total pressure, at fixed power) as reported in Figure 3a. They can be seen as some form of interpolation of the data listed in Table 1. Adopting an active learning approach, conditions of interest were identified that should lead to higher persistence scores. These are situated around 2 Pa and less. Hence, to obtain high color persistence in WO_3, the sputtering conditions need to go toward lower total pressure. Two new experimental tests (samples 13 and 14 in Table 1) were thus conducted adopting a total pressure of 1 Pa. Much higher persistence scores (>0.9) were achieved, confirming the ML predictions.

However, for high-performance WO_3 films, the color persistence should be reversible. A reversibility score was thus also introduced. It is calculated based on the first CV cycle as the ratio of electrochemical capacities in oxidation and reduction, $Q_{oxidation}/Q_{reduction}$, as listed in Table 1. Similar to what was done for the persistence score, an ML model was developed for the reversibility score (Supporting Information),

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Table 1. Set of Experimental Data Used in the Prediction of the Memory Effect Property and Reversibility of 210 nm WO_3 Thin Films

sample	total pressure (Pa)	P_{O_2} (%)	power (W)	ΔT_{48h} (%)	persistence score	reversibility score	global score
1	0.5	2	75	9.8	0.85	0.24	0.20
2	1	2	75	10.5	0.84	0.24	0.20
3	2	2	75	15.8	0.75	0.94	0.71
4	3	2	75	60.4	0.6	0.92	0.05
5	4	2	75	61.1	0.5	0.94	0.05
6	2	0.5	75	43.6	0.32	0.94	0.30
7	2	1	75	38.1	0.41	0.93	0.38
8	2	5	75	15.4	0.76	0.92	0.70
9	2	10	75	32.2	0.50	0.83	0.41
10	2	15	75	35.6	0.45	0.77	0.34
11	2	2	50	64.2	0	0.92	0
12	3	2	50	58.0	0.10	0.93	0.09
13	1	5	75	4.2	0.93	0.23	0.21
14	1	2	50	4.1	0.94	0.31	0.29

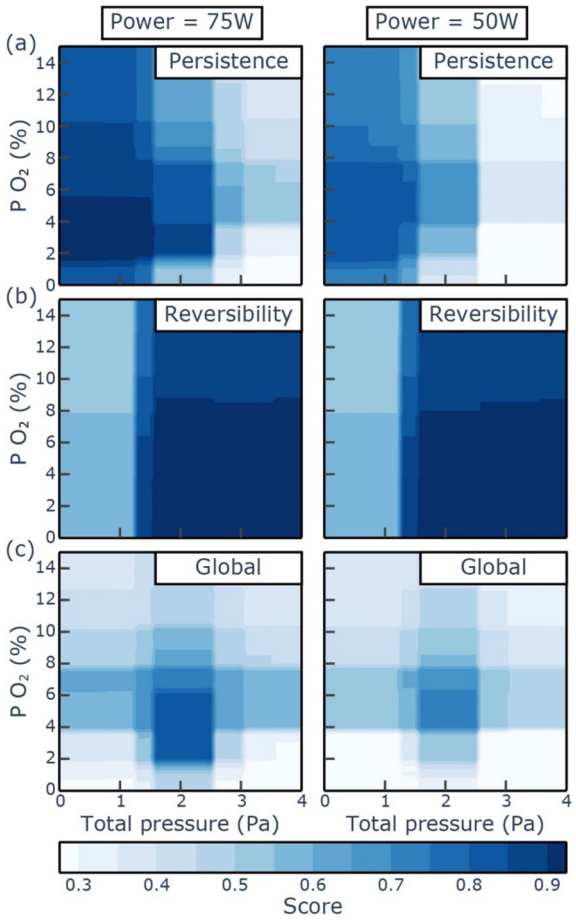

Figure 3. Maps of the (a) persistence, (b) reversibility, and (c) global scores as predicted by the machine learning model trained on the data (samples 1−12) reported in Table 1.

and the maps in Figure 3b were established. These clearly indicate a poor reversibility for total pressure lower than 2 Pa. In other words, to avoid growing WO_3 films with irreversibility, the choice of the sputtering conditions should tend to high total pressure. From these two maps, color persistence and reversibility seem to head toward opposite trends. In order to obtain a compromise, a global score was calculated as the product of the persistence and reversibility scores. The corresponding maps are represented in Figure 3c. It appears that, in a tight window around 2 Pa with an oxygen partial pressure between 2% and 6% of sputtering conditions, WO_3 films with a high color persistence and high reversibility can be prepared. On the basis of these observations, the memory effect property should not correspond only to films with color persistence, but it also needs to present a reversible cycling behavior.

From Figure 3, fixing the power to 75W and the oxygen partial pressure to 2%, an increase of the total pressure from 1 to 4 Pa should allow one to obtain three kinds of films showing (i) blue color persistence and irreversibility, (ii) high blue color persistence and reversibility, and (iii) limited blue color persistence and reversibility. Figure 4a shows the CV of these three kinds of films corresponding to total pressures of 1, 2, and 4 Pa. At 1 Pa, the CV becomes very flat after the first reduction. On the contrary, at 2 and 4 Pa, as predicted, the CVs illustrate a nice reversible process. The shift of the oxidation peak toward higher potential at 2 Pa compared to 4 Pa is related to a higher resistance[24,25] as confirmed by the difficulty of the current density to reach 0 mA/cm^2 at 1 V. On the contrary, for the 4 Pa films, a current density of 0 mA/cm^2 is reached at 0.75 V. For 2 and 4 Pa, similar x values of Li_xWO_3 of around ∼0.5 are calculated. The poor reversibility of the 1 Pa film indicates that most of the Li^+ and electrons are trapped inside the film through the first cycle and cannot be removed upon further oxidation leading to an irreversible blue coloration.

The reversible character of the films deposited at 2 and 4 Pa is correlated with a switch in color from colorless to blue (Figure 1). For the 2 Pa, the slower decrease in current density on CVs is associated with higher switching times deduced from chronoamperometry measurements (Figure 4b). Response time during coloration (reduction) and bleaching (oxidation) correspond to 90% of the current change value as listed in Table 2.[11] The film deposited at 4 Pa reached faster equilibrium (j = 0 mA/cm^2) than the one deposited at 2 Pa. Higher peak current and faster decline indicate a faster electrochemical process.[26,27] In both cases, coloration times are longer than bleaching ones while both are close to twice the ones of 4 Pa for the 2 Pa. This behavior indicates a higher energy barrier to cross during insertion of lithium. WO_3 is a semiconducting material; the lithium insertion leads to a more conductive state due to the coexistence of W^{5+}/W^{6+}. The

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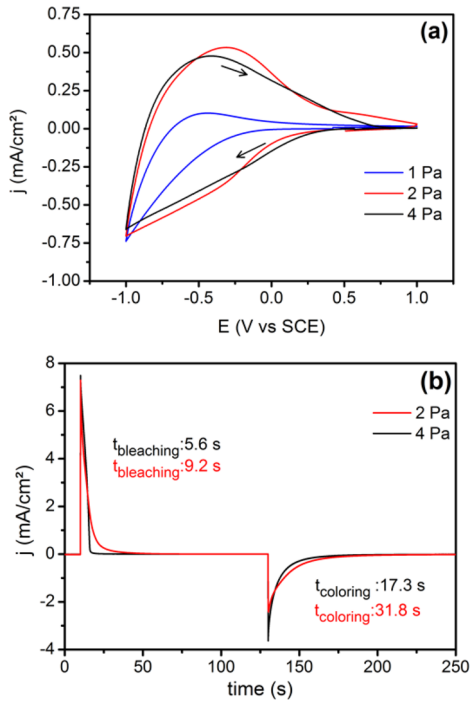

Figure 4. (a) Cyclic voltammograms (1st cycle) for WO_3 thin films deposited at 1, 2, and 4 Pa in WO_3/LiTFSI in EMIMTFSI (1:9 mol %)/Pt vs SCE cell recorded at 20 mV/s. (b) Chronoamperograms of 2 and 4 Pa during bleaching and coloring under +1 and −1 V for 120 s.

Table 2. Switching Times of WO_3 Thin Films Deposited at 2 and 4 Pa

sample	coloring time (s)	bleaching time (s)
2 Pa	31.8	9.2
4 Pa	17.3	5.6

coloring process (eq 1) starts from a bleached WO_3 state which is more resistive than the lithiated state. Since the resistance of the oxidized state is higher, a much longer process is expected to pass from WO_3 to Li_xWO_3 than the reverse.[28,29]

The origin of the various behaviors lies in the film structure, morphology, and composition. Current investigations of the film characteristics are in progress and will be reported in a forthcoming paper.

In summary, combining a machine learning approach to experimental characterizations, based on electrochemical and optical properties, a mapping of the EC performance in the memory effect and reversibility of sputtered WO_3 thin films is successfully proposed. Considering the evolution of three main parameters, power, total pressure, and oxygen partial pressure, ML leads to a complete picture in which experimentalists can identify the relevant set of parameters for the desired EC performance. ML provides a significant gain of time. By considering on average 1 film per day, preparing the total grid of oxygen and total pressure requires the production of a least 30 films at one fixed power where 12 films were sufficient in our case with the help of machine learning.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.jpclett.2c02248.

Detailed information (including the typical errors) of the machine learning models that were developed for the persistence, reversibility, and global scores and information about the active learning approach that was used to define the next experimental attempts (PDF)

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Notes

The authors declare no competing financial interest.

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