Electrochromic energy storage devices

Peihua Yang, Peng Sun and Wenjie Mai*

Siyuan laboratory, Guangzhou Key Laboratory of Vacuum Coating Technologies and New Energy Materials, Department of Physics, Jinan University, Guangzhou, Guangdong 510632, China

Energy storage devices with the smart function of changing color can be obtained by incorporating electrochromic materials into battery or supercapacitor electrodes. In this review, we explain the working principles of supercapacitors, batteries, and electrochromic devices. In addition, we discuss the material candidates for electrochromic energy storages in detail. The challenges of the integrated electrochromic energy system for simultaneous realization of electrochromism and energy storage are specially highlighted.

Introduction

Supercapacitors and batteries are considered two of the most promising energy storage technologies for electric vehicles and renewable energy systems [1–6]. During the charge insertion/ extraction or chemical reduction/oxidation processes, some materials change their colors accordingly, which can be clearly observed when they are fabricated on transparent current collectors. This phenomenon is called electrochromism [7]. Electrochromic materials are gradually attracting significant interest in academia and industry [8,9]. Smart windows, one of the most important types of electrochromic device [10], are essentially transparent rocking-chair batteries consisting of a pair of complementary intercalation layers on the transparent conducting glass, separated by an ion-conducting electrolyte. The similar features of electrochromic devices and batteries/ supercapacitors range from material properties, device construction, and reaction kinetics [11,12]. In this review, we will briefly introduce the mechanism of supercapacitors/batteries and electrochromism with particular focus on the integration and applications of electrochromic energy storage and the corresponding material candidates. The challenges of the emerging integrated electrochromic energy system for simultaneous realization of electrochromism and energy storage will be specially highlighted.

Principles and applications

Supercapacitors and batteries

In Li-ion batteries, one of the most important batteries, the insertion of Li^+ that enables redox reactions in bulk electrode materials is diffusion-controlled and thus slow, leading to a high energy density but a long recharge time. Supercapacitors, or named as electrochemical capacitors, store electrical energy on the basis of two mechanisms: electrical double layer effect on material surface in electrical double layer capacitors (EDLCs) (Fig. 1a and b), and fast bidimensional redox reactions (Fig. 1c) or rapid tridimensional intercalation processes (Fig. 1d) in a very thin surface layer in pseudocapacitors. Based on the unique energy storage mechanisms, supercapacitors can be charged and discharged at a much higher rate than batteries.

The different electrochemical processes occurring in batteries and supercapacitors lead to their different charge-storage properties, and electrochemical measurements can distinguish their different mechanisms [13]. There is no redox reaction in EDLCs, so the current response to potential change is rapid, which leads to the high power density; but the charges are confined to material surfaces, resulting in the low energy density. The classic rectangular cyclic voltammogram (CV) curve (Fig. 1e) and linear time-dependent discharge curve (Fig. 1g) are two main characteristic features of EDLC. In contrast, the CV curves are characterized by faradaic redox peaks in batteries because of phase transitions (Fig. 1f), meanwhile, the presence of two phases is also indicated by the voltage plateau in discharge experiments (Fig. 1f). As in

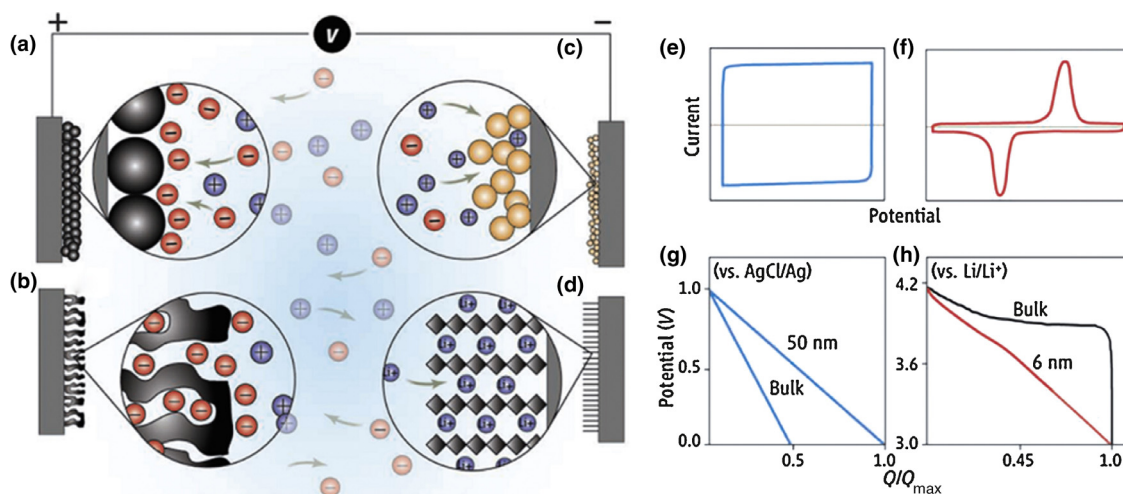*Corresponding author. Mai, W.J. (wenjiemai@gmail.com)

FIGURE 1

Comparison of batteries and supercapacitors. (a–d) Schematic illustration of different mechanisms of capacitive energy storage. (e–h) Electrochemical characteristics distinguishing supercapacitor and battery materials from CV curves and liner time dependent discharge curves. Reproduced with permission from Ref. [13]. Copyright 2014, American Association for the Advancement of Science.

previous reports, Conway recognized that reversible redox reactions occurring at or near the surface (bidimensional) of appropriate materials (e.g. RuO_2 and MnO_2) lead to EDLC-like electrochemical features [14] and Dunn et al. supplemented the fast intercalation (tridimensional) pseudocapacitors based on the research of Nb_2O_5 [15]. Pseudocapacitive materials can achieve battery-level energy density and combine the long cycle life and high power density. Despite the clear definition, many battery-type electrodes such as $Ni(OH)_2$, which exhibit faradaic behavior, have been presented in previous literatures as pseudo-capacitive materials. Such presentation leads to confusion because the concept of ''capacitance'' (F) cannot be applied to pure faradaic behavior, where ''capacity'' (coulomb, C, or mAh) is the most appropriate and meaningful metric to use in such cases [16]. It is worth noting that the scale of materials has a powerful influence on their electrochemical properties and some battery materials (for instance, $LiCoO_2$) can behave like supercapacitors when they are in nanoscale (lower curve in Fig. 1h), which is nominated as extrinsic pseudocapacitance [17]. Anyway, supercapacitors and batteries that rely on electrochemical processes are two important power sources which have crucial influence in our daily life [18,19].

Electrochromic devices

Electrochromism, evocating the alteration of color by passing a current or applying a potential to special materials, has been greatly advanced over the past years, providing widespread applications in light-regulation and displays [20,21]. It is noteworthy that spectral change accompanying a redox reaction is visually indiscernible if the optical absorptions fall in the ultraviolet or infrared wavelength. When the change is in the visible region, then a definition of electrochromism can be formulated as coloring or bleaching effected by an electron-transfer process.

To compare performance among different electrochromic materials and devices, researchers use the coloration efficiency as a key parameter. Coloration efficiency (CE) is given by

$$CE(\lambda) = \frac{\Delta OD}{Q} = \frac{\log(T_b/T_c)}{Q} \qquad (1)$$

where Q is the electronic charge inserted into or extracted from the electrochromic material per unit area, ΔOD is the change of optical density, T_b is the transmittance in the bleached state, and T_c is the transmittance in the colored state [22]. Since the transmittance depends on the wavelength of observation, CE must be determined at a fixed wavelength (λ); Q is defined as positive if color is generated cathodically (charge insertion), and negative if color is generated anodically (charge extraction) [7], which is in accordance with the International Union of Pure and Applied Chemistry (IUPAC) definitions: anodic currents are deemed negative, and cathodic currents are positive.

While the applications of electrochromism are ever growing, all devices utilizing electrochromic color modulation fall within two categories according to the modes of transmission and reflection. Svensson and Granqvist coined the term ''smart window'' to describe windows that own electrochromism character, meaning they can change transmittance under different voltage [23,24]. The appeal for smart windows is both in economic and environmental angles: if mature, they can be employed to properly modify sunlight into a room or a building for saving energy or preclude much solar radiation to avoid light pollution [25,26]. Figs. 2 and 3a describe the configuration of electrochromic device and mechanism of electrochromic window, respectively [22,27]. In the electrochromic window design, the window is an electrochemical cell in which two conducting glass panes are separated by an electrolyte material. At open circuit voltage, the window is in Bright Mode, that is, both work and counter electrodes are transparent to solar radiation, allowing heat and natural light to enter the room. When the voltage is reduced to an intermediate value, the window switches to Cool Mode, blocking heat while allowing natural light to enter the room. At lower potentials, the window switches to Dark Mode, limiting the amount of heat and natural light that
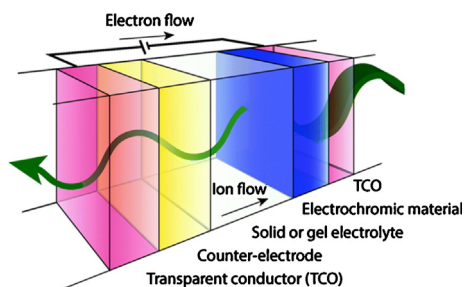
FIGURE 2

Schematic of the electrochromic device. Electrons flow through an external circuit into the electrochromic material, while ions flow through the electrolyte to compensate the electronic charge. Reprinted with permission from Ref. [22]. Copyright 2014, Royal Society of Chemistry.

enters the room. These three switching modes enable the window to operate at different weather conditions, which is helpful for energy savings and comfort. Most people preferred to control the external light via electrochromic windows rather than blinds or other mechanical forms of shutter because smart windows give users the ability to tune optical transmission from clear to dark. Boeing has installed electrochromic windows in the new long-range Boeing aircraft, the ''Dreamliner''. The windows are said to be 25% greater in area than the usual ones. Fig. 3b shows that the smart window allows passengers to modulate it from clear to five increasing levels of darkening states up to virtual opacity. For self-powered system of smart windows, a proof-of-concept experiment involving an integrated color-changing system consisting of solar cells and electrochromic devices has been designed and demonstrated [28]. Recently, Cannavale et al. reported a perovskite-based photovoltachromic device with self-adaptive transparency [29], which is capable of producing electrical power by solar energy

conversion as well as undergoing an electrochromic transition from neutral-color semi-transparent to dark blue-tinted when irradiated by solar light, without any additional external bias. The result represented a significant step toward the commercialization of smart windows for buildings or transportation tools. Electrochromic sunglasses also operate in a transmission mode. Osterholm et al. created a set of brown electrochromic polymer blends that can be incorporated as the active material in user-controlled electrochromic eyewear (Fig. 3c) [30].

Mirrors, which obviously operate in a reflection mode, illustrate another application of electrochromism [31]. Gentex introduced an automatic dimming mirror based on electrochromism. It can automatically darken to reduce glare from the headlamps of vehicles approaching from the rear. The brighter the glare, the darker the mirrors become, ensuring the safety of the nighttime driving (as illustrated in Fig. 3d).

Electrochromic devices operating as displays can act in either reflection or transmission modes, with the majority being the reflection type [20]. Electrochromic devices are often termed ''passive'' since they do not emit light and require external illumination, a possible disadvantage compared to other emissive displays: light emitting diodes and cathode-ray tubes (CRT). But liquid crystal displays (LCD) and almost all mechanical displays are also non-emissive [7]. Electrochromic devices have been proposed as flat-panel displays in applications such as television, data boards at transport terminuses and even advertising boards. Electrochromic devices can compete with LCDs for commercial viability, and therefore possess economic advantages over them. The obvious advantages are shown as follows: firstly, electrochromic devices consume little power in producing images which, once formed, require little or no additional input of power; secondly, in principle, there is no limit to the size of an electrochromic device,
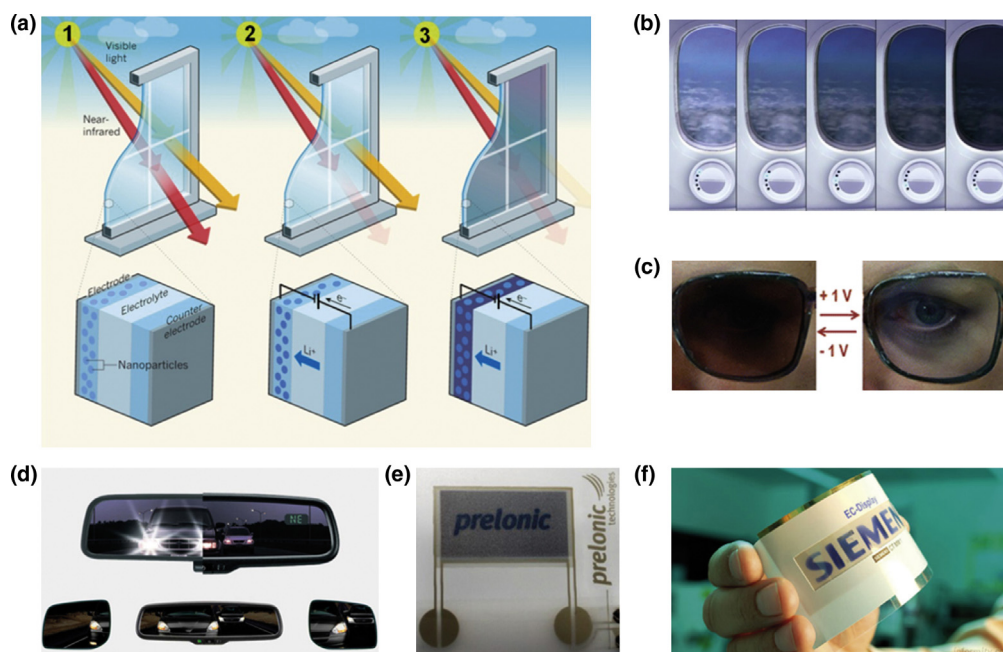

FIGURE 3

Applications of electrochromic devices. (a) Design of electrochromic window. Reprinted with permission Ref. [27]. Copyright 2013, Macmillan Publishers. (b) Smart switchable window applied in Boeing aircraft produced by SmartTint®. (c) Photographs of the electrochromic lens. Reprinted with permission from Ref. [30]. Copyright 2015, American Chemical Society. (d) Automatic dimming mirror based on electrochromism produced by Gentex®. Printable and flexible electrochromic displays designed by (e) Prelonic Technologies® and (f) Siemens®.

so a device can be constructed having a larger electrode expanse. Recently, Prelonic Technologies and Siemens have announced a new printable and flexible electrochromic display (Fig. 3e and f). The new displays are not only low-cost, but can also be produced in normal printing processes. Additionally, they can be bottom and top indicative, which allows us to print directly on paper. The attention on applications of electrochromic materials has shifted from small scale display devices to large scale transmissive and reflective devices in recent years.

Integration possibility

A typical electrochromic configuration, depicted in Fig. 2, is a multi-layer device consisting of an active electrochromic electrode layer, a counter electrode layer, an electrolyte layer, two transparent conducting layers, and the supporting substrates. Devices designed with this structure can be regarded as an ''electrical thin-film battery'' with a charging state that translates to a degree of optical absorption. This analogy has been mentioned before, and electrochromic devices and batteries have many characteristics in common [11,32–36].

Pseudocapacitors and batteries are generally associated with faradic reactions at the electrode surface and bulk, respectively, through which charges are stored. When a faradic reaction occurs with charge transfer, some electrode materials will reversibly change color. This phenomenon is known as electrochromism. Considering the electrochromic process happens when the charge injects or ejects, electrochromic devices can be integrated with charge storage devices. Here we emphasize the combination of energy storage and electrochromism, achieving both advantages in these two associated effects, as illustrated in Fig. 4. Since the electrochromic device is also an electrical thin-film battery, the operating life of the electrochromic device is related to the lifetime of the battery (or capacitor).

The combination concept falls into two aspects. Firstly, making an energy device such as a supercapacitor or a battery changes its color according to its charged state conforms to the concept of intelligence, and the state of charge can be monitored by simple visual inspection. If an energy storage device can sense energy changes in a predictable mode, we may quickly determine that the energy has been exhausted before a device stops working,
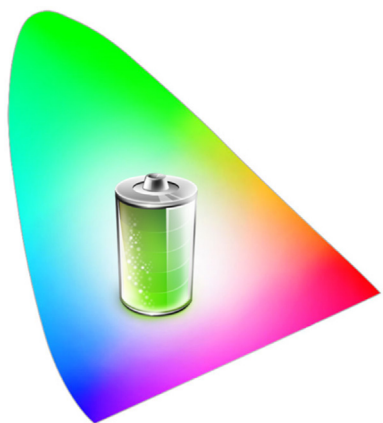

FIGURE 4

The concept of combining energy storage and electrochromism, achieving both of advantages in these integrated systems.

demonstrating a wide range of potential intelligence applications. Secondly, utilizing the energy stored in electrochromic devices saves energy. If we need to color the electrochromic device in order to resist sunshine or protect privacy, charges can be stored in it. When the colored state is not necessary, the stored energy can be released through an external circuit, providing another thought of energy resources utilization.

Materials candidates
Metal oxides

Research and development on electrochromic materials and their applications has been continuing since the discovery of electrochromism [37,38]. Concerning electrochromic oxides, focuses on them show an explosive growth. There are two principally different kinds of electrochromic oxides: those referred to as ''cathodic'' color under ion insertion, and the ''anodic'' ones color under ion extraction [7]. Applying a voltage in order to transport ions between the electrochromic films along one direction makes both of these films color, and transporting ions in the other direction makes both of them bleach; this can be referred to as ''rocking chair'' process from lithium battery technology.

The most commonly used cathodic electrochromism oxides are mainly based on tungsten oxides [39–46]. The schematic reaction can be summarized as the equation below,

$$[WO_3 + H^+ + e^-]_{bleached} \leftrightarrow [HWO_3]_{colored} \qquad (2)$$
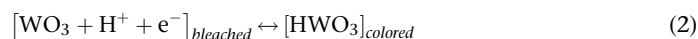
which is the case of proton insertion/extraction. Very recently, tungsten oxide for pseudocapacitor and electrochromic applications has drawn tremendous attention [47–49]. For instance, Yang et al. designed multifunctional glass windows that combine energy storage and electrochromism using WO_3 film electrodes which were obtained by facile thermal evaporation method (Fig. 5a–c) [50]. These WO_3 films exhibited a high specific capacitance of 639.8 F g^{-1}. Their color changed from transparent to deep blue with an abrupt decrease in optical transmittance from 91.3% to 15.1% at a wavelength of 633 nm when a voltage of −0.6 V (vs. Ag/AgCl) was applied, demonstrating its excellent energy storage and electrochromism properties. The coloration efficiency of WO_3 electrodes reached 54.8 cm^2 C^{-1}. What's more, a large scale pseudocapacitive WO_3-based glass window (15 cm × 15 cm) was fabricated as a prototype. Thereafter, they quantitatively investigated the charge storage process of tungsten oxide film [51]. It is noteworthy that WO_3 film usually suffers from ion-trapping-induced degradation of optical modulation and cycle reversibility on prolonged cation ion exchange, and this effect can be successfully eliminated by constant-current-driven de-trapping, providing a general framework for developing and designing superior electrochromic devices [52]. Such smart pseudocapacitive glass windows show great potential in functioning as electrochromic windows and concurrently powering electronic devices. Lately, Xie et al. designed a self-powered electrochromic smart window with tunable transmittance driven by dye-sensitized solar cells, which also acts as a photocharged electrochromic supercapacitor with high areal capacitance and color changes reversibility [53].

Niobium oxide (Nb_2O_5) is another cathodic electrochromism oxide, and the charge-storage mechanism of intercalation pseudocapacitance is characterized as an intrinsic property of Nb_2O_5

that facilitates the design of electrodes for capacitive storage devices [54,55]. Milliron et al. developed synthetic protocols for incorporating Nb_2O_5 nanocrystals, and they achieved this approach by introducing tin-doped indium oxide nanocrystals into Nb_2O_5 glass, realizing a new amorphous structure (Fig. 5d and e) [56]. The coloration efficiency was calculated to be 30 $cm^2 C^{-1}$ (at 500 nm). The resulting material demonstrates a previously unrealized optical switching behavior that will enable the dynamic control of solar radiation transmittance through windows.

TiO_2 is also a promising material currently being used in cathodic electrochromism because the vacant sites formed by the shared edges are large enough to accommodate protons and Li^+ ions [28,57]. Giannuzzi et al. synthesized a novel class of anisotropic TiO_2 (B) nanocrystals, which was profitably exploited to fabricate highly efficient electrodes for lithium storage (Fig. 5f) [58]. The outstanding lithiation/delithiation capabilities were utilized to fabricate electrochromic devices that revealed an excellent coloration efficiency (130 $cm^2 C^{-1}$ at 800 nm) at a voltage of 1.5 V, as well as an extremely fast electrochromic switch (coloration time 5 s).

The anodic electrochromism oxides are mainly based on nickel oxide and the schematic reaction can be summarized in the following equation,

$$[NiOOH + H^+ + e^-]_{colored} \leftrightarrow [Ni(OH)_2]_{bleached} \tag{3}$$

for illustrating the case of proton insertion/extraction. NiO is an attractive and effective electrochromic material due to its good cyclic reversibility and low cost [39,59,60]. Xia et al. prepared porous nickel oxide thin films on ITO glass by a simple chemical bath deposition method and a subsequent heat-treatment process [61]. The NiO film annealed at 300 °C exhibited a noticeable electrochromism and good memory effect. The coloration efficiency was calculated to be −42 $cm^2 C^{-1}$ (at 550 nm), with a variation of transmittance up to 82% (Fig. 6a). According to previous clarification, NiO is identified as a kind of battery-type materials. Wen et al. prepared a new kind of NiO_x ($1.16 \leq x \leq 1.32$) films by sputter deposition [62]. The electrochromism is significantly enhanced at large values of x. It has been found that charge exchange in nickel oxide is mainly due to surface processes, which is different from previous reports of NiO (Fig. 6b). Whereas previous studies of nickel oxide have been focused on cation intercalation, the surface processes-based mechanism presented here offers a new paradigm for designing and developing electrochromic and energy storage devices.

For supercapacitor application, manganese oxide (MnO_x) has significant advantages, such as abundant resource, low cost, easy fabrication procedure and high theoretical specific capacitance [63–68]. Meanwhile, the redox processes induce changes in the UV–visible absorption spectra of MnO_2 electrodes, exhibiting anodic electrochromism [69,70]. Chigane et al. deposited MnO_x on transparent conducting tin oxide glass substrates [71]. In the early 1000 cycles of switching test between 0.5 and −0.2 V, both absorbance of the film at 400 nm in the oxidized and reduced states increased. In view of the sufficient electrochromic operation durability within 10,000 cycles, with a comparable coloration efficiency (−41.7 $cm^2 C^{-1}$ at 400 nm), there would be a high possibility in application of the MnO_x film to both light modulating and energy storage devices.
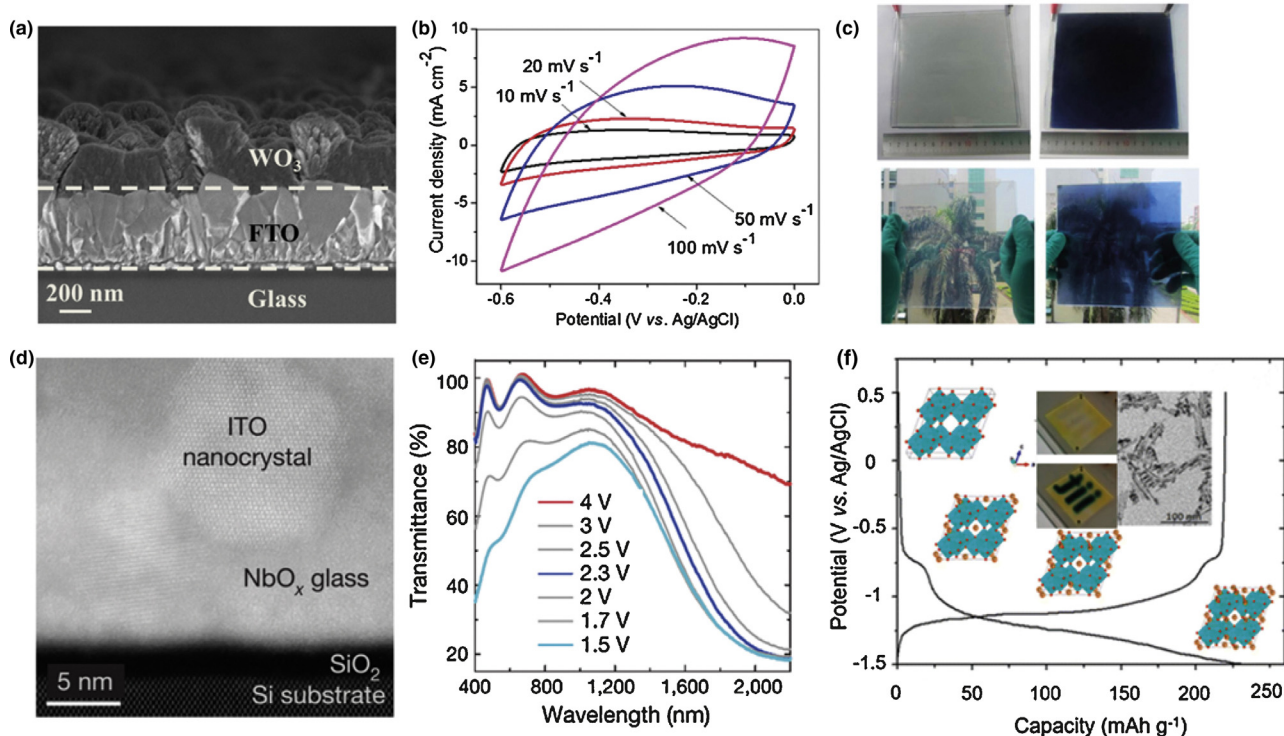

FIGURE 5

Cathodic electrochromism oxides. (a–c) Multifunctional glass windows that combine energy storage and electrochromism using WO_3 film electrodes. Reprinted with permission from Ref. [50]. Copyright 2014, John Wiley and Sons. (d) Structure and (e) transmittance spectra of a typical ITO-in-NbO_x film. Reprinted with permission Ref. [56]. Copyright 2013, Macmillan Publishers. (f) Battery behavior and electrochromism demonstration of TiO_2 (B). Reprinted with permission from Ref. [58]. Copyright 2012, American Chemical Society.
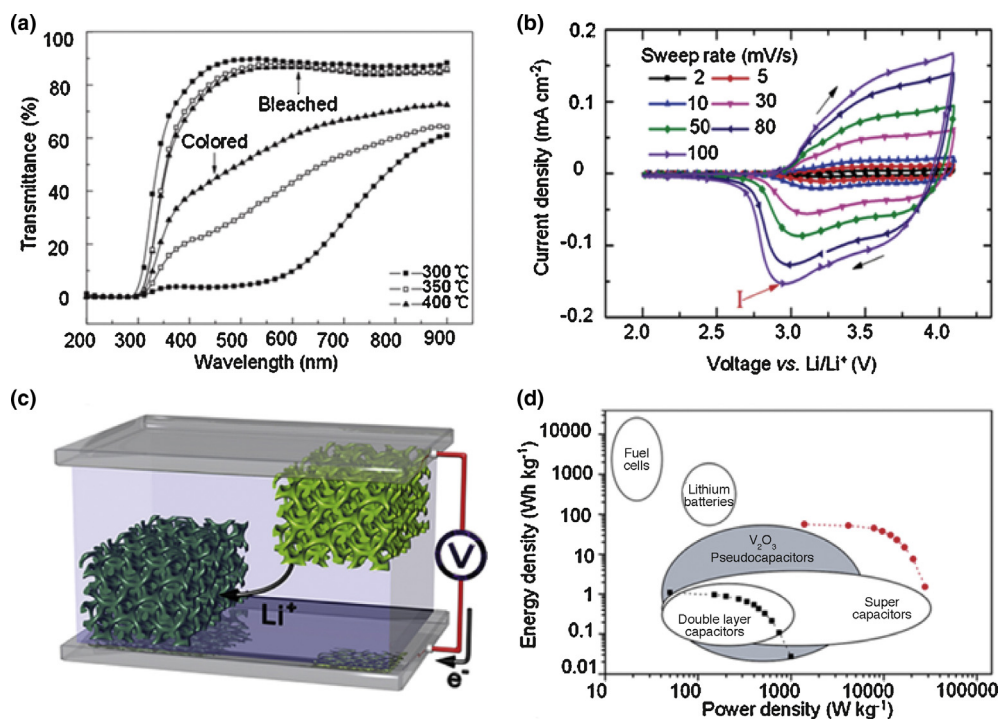
FIGURE 6

Anodic electrochromism nickel oxides and special vanadium pentoxide. (a) Optical transmittance spectra of prepared NiO thin films by a chemical bath deposition method. Reprinted with permission from Ref. [61]. Copyright 2008, Elsevier. (b) Electrochemical performance of cation/anion-based surface processes controlled NiO_x films. Reprinted with permission from Ref. [62]. Copyright 2015, John Wiley and Sons. (c to d) Schematic design illustration and Ragone plot of the gyroid V_2O_5 electrochromic supercapacitor. Reprinted with permission from Ref. [75]. Copyright 2012, American Chemical Society.

Finally, a special metal oxide, vanadium pentoxide (V_2O_5), which combines cathodic and anodic electrochromism, has a principally different electronic structure and the electrochromism mechanism has been fully discussed in previous literatures [39,72,73]. Steiner group reported a successful application of an ordered gyroid-nanostructured V_2O_5 network in an electrochromic supercapacitor (Fig. 6c and d) [74,75]. The highly ordered nanostructure is ideal for fast and efficient lithium ion intercalation/extraction and faradaic surface reactions, which are vital for high power and high energy density electrochemical energy storage. Supercapacitors made from the vanadia electrodes exhibited a high specific capacitance of 155 F g^{-1} in lithium salt electrolyte and showed an obvious electrochromic color change from green to yellow, indicating the capacitor's charge degree. Furthermore, they presented a design for a reusable light indicator based on gyroid-structured nickel oxide electrochromic display using a similar strategy [76,77].

Conducting polymers

Electrochromic metal oxides with drawbacks such as slow switching times and poor coloration efficiencies are facing stiff competition from conducting polymer materials which have long been in focus because of the low cost, fast preparing process and remarkable electrochemical properties [78–80]. Polyaniline (PANI) films are generally prepared from aqueous solutions of aniline in acids, and have been widely explored in applications of electrochromism and supercapacitors [81–83]. Several redox mechanisms involving protonation/deprotonation or anion ingress/egress have been proposed. PANI films exhibit the following reversible color

changes as the potential is varied: transparent leucoemeraldine to yellow-green emeraldine to dark blue-black pernigraniline, in the potential ranging from −0.2 to +1.0 V vs. SCE [84]. Wang et al. designed a new integrated multifunctional flexible device using ordered PANI nanowire arrays as electrodes and called it "energy storage smart window" (Fig. 7a–d) [85]. The smart window showed high areal capacitance (0.017 F cm^{-2} at 5 mV s^{-1}) and high stability as a supercapacitor, and optical measurements proved its electrochromic function. This proposed smart window can potentially be applied as a smart window or shutter for rooms, roofs, and cars.

Polypyrrole (PPy) is also extensively studied for their electrochromic and electrochemical properties [86–89]. Thin films of PPy are yellow-to-green in the undoped insulating state and blue-to-violet in the doped conductive state [90]. As an important derivative, poly(3,4-ethylenedioxypyrrole) or PEDOP, is potentially valuable owing to a lower oxidation potential (1.2 V vs. NHE). Reddy et al. fabricated PEDOP-Au@WO_3 electrochromic supercapacitor electrode that is capable of optically modulating solar energy while simultaneously storing/releasing energy (Fig. 7e) [91]. In situ optical transmittance spectra of PEDOP-Au@WO_3 film as functions of applied potential and time are shown in Fig. 7f, illustrating the simultaneous electrochromic and pseudocapacitive capabilities. It is optimistic that the robust combination strategy could enable the fabrication of conducting polymer for combined applications in optical coating and electrochemical energy storage [92–95].

Inorganic non-oxides

Prussian blue (PB), or iron (III) hexacyanoferrate (II), is extensively used as a pigment in the formulation of paints, lacquers and
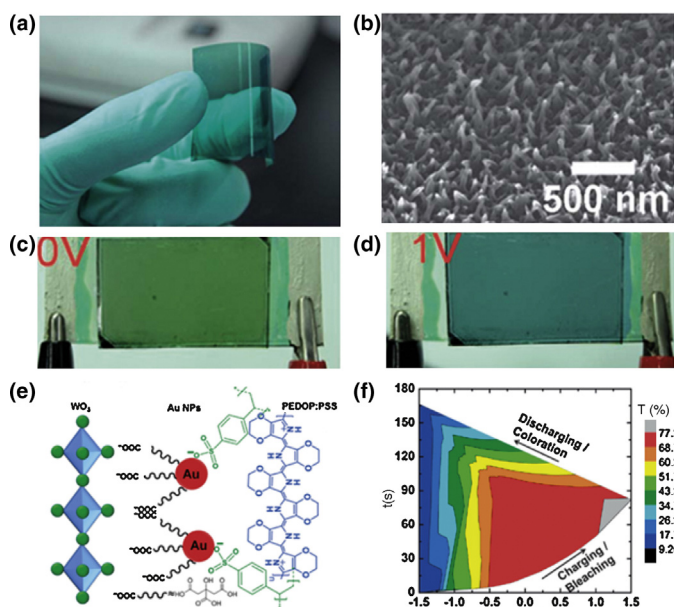
FIGURE 7

Polymer electrochromic materials. (a–d) Energy storage smart window based on PANI. Reprinted with permission from Ref. [85]. Copyright 2012, Royal Society of Chemistry. (e) Schematic of WO3-Au-PEDOP interactions and (f) *in situ* optical transmittance spectra as a function of applied potential and time. Reprinted with permission from Ref. [91]. Copyright 2015, John Wiley and Sons.

printing inks. Since the first report of the electrochemistry of PB films, numerous studies concerning the electrochemistry of PB and related analogs have been conducted. In addition to applying them in electrochromism, there are also proposed applications in electrocatalysis and energy storage. Cui group has introduced a family of cathodes involving the reversible insertion of cations into materials with the PB open-framework crystal structure [96,97]. They recently reported a newly developed manganese hexacyanomanganate open-framework anode that has the same crystal structure as PB [98]. Besides, Lou group developed a self-powered electrochromic window, which can be used as a self-rechargeable battery [99]. They used aluminum to reduce PB to Prussian white (PW, colorless) in potassium chloride electrolyte, realizing a device capable of self-bleaching. The device can be self-recovered (gaining blue appearance again) by simply disconnecting the aluminum and PB electrodes, which is due to the spontaneous oxidation of PW to PB by the dissolved oxygen in aqueous solution. The self-operated bleaching and coloration suggests an important function of the device: a self-rechargeable transparent battery (Fig. 8a and b).

Graphene-based materials are becoming increasingly popular for applications in the area of energy storage and conversion [100,101], and their gate-tunable optical properties have become an active research focus in optoelectronics. Polat et al. investigated an optical modulation scheme using graphene supercapacitors
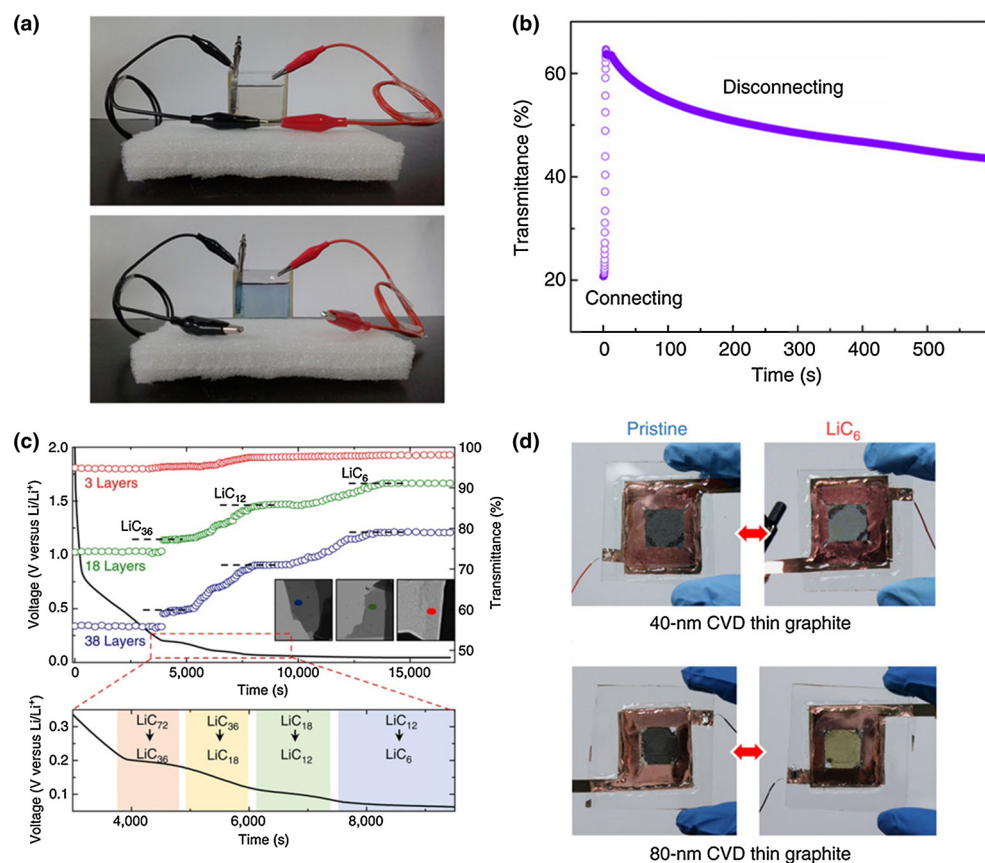

FIGURE 8

Electrochromic energy storage devices based on Prussian blue and graphene. (a) Optical photos of the bleached and colored electrochromic smart windows based on Prussian blue. (b) *In situ* transmittance measurement of the electrochromic device. Reprinted with permission Ref. [99]. Copyright 2014, Macmillan Publishers. (c) Optical transmittance evolution during Li intercalation process in graphene. (d) Demonstration of encapsulated large-area transparent electrode before and after Li intercalation. Reprinted with permission Ref. [104]. Copyright 2014, Macmillan Publishers.

[102], and lately demonstrated a new class of flexible electrochromic devices using multilayer graphene [103]. Recently, Hu et al. measured *in situ* optical transmittance spectra and electrical transport properties of ultrathin graphite (3–60 graphene layers) simultaneously during electrochemical lithiation/delithiation processes (Fig. 8c) [104]. On intercalation, they observed an increase of both optical transmittance (up to twofold) and electrical conductivity (up to two orders of magnitude), strikingly different from other materials. The methodology reported in the study can be applied to *in situ* investigations of the electrochromic performance during the intercalation process with good spatial and temporal resolution in large area materials for electrochemical energy storage applications (Fig. 8d).

Challenges and outlook

Electrochromic energy storage devices change their color while they store energy, which can be used in buildings and automobiles. Electrochromic devices and energy storage devices have many aspects in common, such as materials, chemical and structure requirements, physical and chemical operating mechanism. The charge and discharge properties of an electrochromic device are comparable to those of a battery or supercapacitor. In other word, an electrochromic device is a rechargeable battery with transparent electrodes. Although many analogies exist in regard to the mechanism of the energy supplying processes in batteries and electrochromic device, they also exhibit some differences. One of the most important operating parameter of an electrochromic device is coloration efficiency as described in Eq. (1). A high coloration efficiency and high speed of the switching processes require a low charge density for a high response in the optical density. However, batteries or supercapacitors must show a high charge density. This is the basic contradiction of electrochromism and energy storage. In the current situation, the combination of electrochromism and energy storage is accomplished by taking moderate performance of these two kinds of devices. Few researchers focused on the energy supplying processes when the electrodes change color under a potential, hence, only the application of electrochromism function is elaborated above. We hope, in the future, advanced technologies and new materials will bring us excellent performance devices that integrate electrochromism and energy storage.

Acknowledgements

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