

Chapter 9

Characteristics of Electrode Materials for Supercapacitors



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Abstract Device performance is based on the individual properties of the materials and performance of the components in the working environments. For example, the fabrication of high-performance supercapacitors and the electrode material should have a high specific surface area and high electrical conductivity along electrical and thermal stability. For different charge storage mechanisms in supercapacitors like electrical double-layer capacitors, pseudocapacitors and hybrid capacitors, and different types of electrode materials are proposed. Electrode materials of a supercapacitor decide the storage of charge in the device and thereby the capacitance of the final device. The effective surface area including electrical conductivity remains the parameter of importance to produce high capacitance. Carbon materials are proposed as the electrode material by storage of the charge at the surface of the material via electrical double-layer capacitance. High surface area, appropriate pore size, pore size distribution and the presence of functional groups complement the capacitance of the device. Some commonly used carbon-based materials of interest are graphite, graphene, carbon nanotube, activated carbon, etc. Other materials of importance remain metal oxides, conducting polymers, metal–organic frameworks, MXenes, black phosphorus, metal nitrides, etc. This chapter provides a short yet comprehensive overview of the characteristics of suitable electrode material for supercapacitor

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devices. Activated carbon, carbon nanotubes, graphene, polyaniline (PANI), polypyrrole (PPY) and polythiophene (PTH) are examples of some of the suitable electrode materials.

9.1 Introduction

Every material has its specific property and limitation. Properties of a material govern the specific performance and its potential applications. It is rare that the performance of material depends only on one property; in contrast, it is always the combination of different properties. For better performance of a device, it is necessary to know the variation of one property against other property to understand the limitations and correlations among the material properties.

Nowadays, energy storage devices are an important area for research so that the various smart devices can be made to overcome the energy crises of the present age. A new technology, known as supercapacitor, has emerged with an excellent ability to store energy. It utilizes the properties of high surface area electrodes and thinner dielectrics to attain higher capacitance value. Supercapacitor follows the same governing equations, which are used for conventional capacitors. It is an electrical storage device having high energy storage density simultaneously with a limited-power density (compared to capacitor). As a result, supercapacitors may become an attractive power solution for an increasing number of applications. The supercapacitors have the capability of delivering high power as compared to the batteries. It has capacitance much higher than the conventional capacitors that bridges the gap between electrolyte capacitors and rechargeable batteries. It provides a hundred to thousand times of high power as compared to the conventional batteries having the same volume and delivers charges at must faster rate. Hence, supercapacitors are suitable materials for those application areas, where high power is needed. Applications where rapid charge/discharge cycles are required rather than long term energy storage, supercapacitors are the material of interest. There are two major developments in the area of supercapacitors: The first device is electrochemical double-layer capacitors (EDLCs), and the other is the pseudocapacitors. EDLCs store charges by the formation of an electrochemical double layer at the electrode/electrolyte interfaces, whereas pseudocapacitors use electron transfer mechanisms such as Faradaic reactions to store charges [1–3].

In the context of high-performance supercapacitor, for the material selection of supercapacitors, it is necessary to take care of four components. These are current collector, electrode, electrolyte and separator. Supercapacitor performance depends on the selection of materials of these four elements. But this chapter discusses the characteristics of electrode materials used in supercapacitors.

9.2 Historical Background of Supercapacitors

The history of supercapacitors is not very old; however, within a small span of time it has received a lot of attention. In 1853, Hermann von Helmholtz has introduced electric double-layer capacitor (EDLC), which stores charge electrostatically at the electrode and electrolyte interface. Practical use of electrostatic double-layer capacitance has been accomplished after filing a patent on the porous carbon-based capacitor in the year of 1957 by Becker at the General Electric Corporation (Becker 1957). For commercial purpose, the first supercapacitor based on porous carbon and tetra alkaline ammonium salt has been manufactured by the Sohio Corporation (now called BP), Cleveland, in the year of 1969. Sohio Corporation abandons its further marketing, and the license of manufacturing has been given to NEC Corporation (Japanese multinational provider of information technology services and products). NEC Corporation has successfully marketed a supercapacitor for the memory backup of computers [4]. Pseudocapacitor is introduced in the year of 1971. Storage of the proton on the surface of thin-filmed RuO_2 surface results in a fast Faradaic reaction called pseudocapacitor [5]. Till the year of the 1990s, many companies have been introduced in the field of supercapacitor, which provides improved performance and low-cost supercapacitor for hybrid vehicles [4]. For energy density improvement of supercapacitor, a hybrid capacitor comes into the picture with one capacitor-type electrode and other battery-type electrode [6–8].

9.3 Types of Supercapacitors

Electrochemical capacitor stores charge electrostatically on the surface of the electrode material, unlike the battery, where phase change takes place. Here, charge accumulates at the interface of the high surface area electrode and the electrolyte. Because of the physical storing of the charge, the process is fast and highly reversible. When it is connected with the external source, the electrolyte ions get collected over the electrode surface. The electrodes already have a particular charge either positive or negative, and opposite ions get accumulated on the electrode also called electric double-layer capacitor. Electrolyte ions and electrode surface are separated by the solvent molecules, which act as a dielectric material. Solvent molecules make a single layer over the surface of electrolyte ions called solvation. Solvation occurs because of hydrogen bonding, van der Waals forces and ion–dipole interactions. Some ions pass through the solvent layer and intercalate or adhere to the surface of electrode, and fast Faradaic reaction takes place called pseudocapacitor. Figure 9.1 demonstrates types of supercapacitors like EDLCs, pseudocapacitor, hybrid capacitor with their corresponding electrode materials.

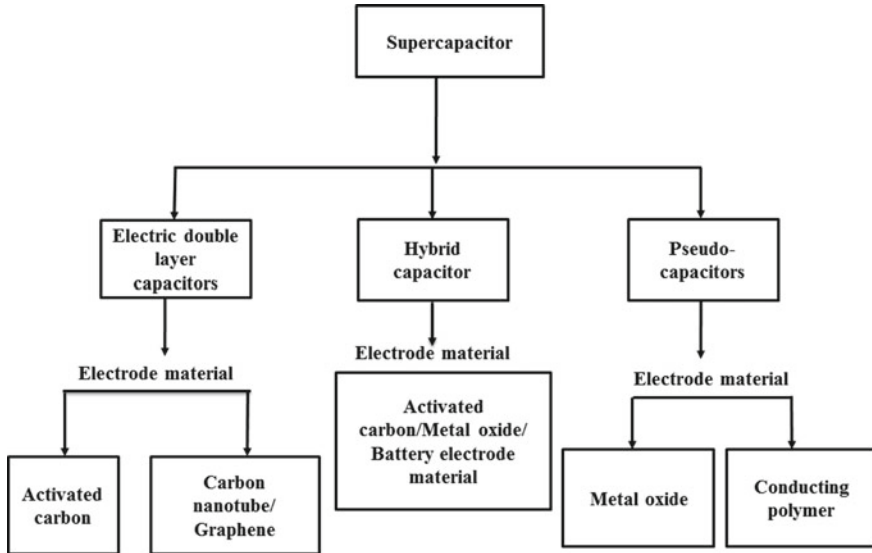


Fig. 9.1 Types of supercapacitor with commonly used electrode material

9.3.1 Electric Double-Layer Capacitors

During charging, EDLC stores ions at the interface of the electrode and electrolyte by fast ion adsorption [9]. In EDLCs, non-Faradaic and highly reversible charge–discharge reactions take place, which manifest mirror image voltammograms [9–11]. The charge storage mechanism in EDLC is based on three models: Helmholtz model, Gouy–Chapman model and Stern model (Fig. 9.2). Helmholtz model considers that two parallel layers of opposite charges form at the interface of the electrode and electrolyte (Fig. 9.2a). It is stated that the potential window varies linearly till the outer Helmholtz layer. Gouy–Chapman model considers the thermal motion of the ions, which forms a diffused double layer at the surface of the electrode material instead of closely packed ions on the surface of electrode material (Fig. 9.2b). Again, the potential varies exponentially in this case. Stern model is the combination of the Helmholtz and Gouy–Chapman models. This model concludes that there will be compact ions on the electrode surface (Helmholtz model) and next to it there will be a diffused layer of ions (Gouy–Chapman model). Here, the potential varies linearly till the outer Helmholtz layer and then exponentially in the diffused layer (Fig. 9.2c). Equivalent capacitance in the Stern model is a series combination of the capacitance of the charges held inside the outer Helmholtz layer and capacitance of the diffused layer [12]. EDLC is known for its high power capability and cycle life, while pseudocapacitor provides high capacitance and high energy density [9]. For high EDLC, the porosity of the electrode material and electrolyte ion size plays an important role [13].

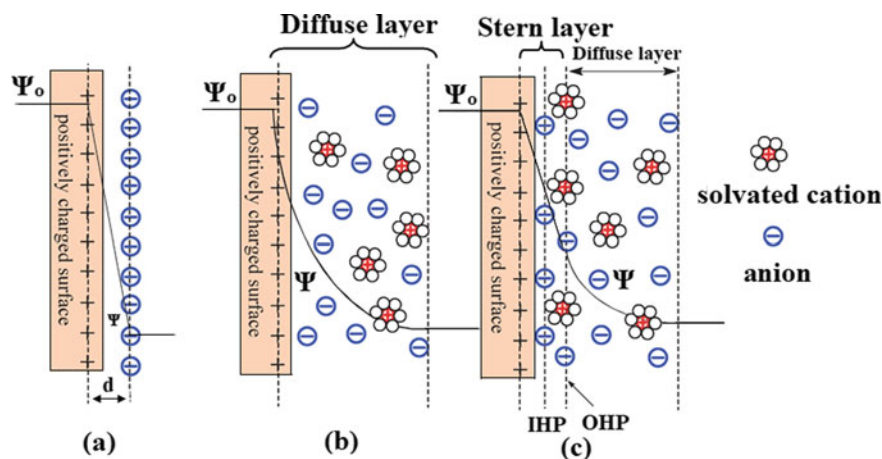


Fig. 9.2 Charge and potential distribution in Helmholtz, Gouy–Chapman and stern model. Redrawn and reprinted with permission from [14]

Accumulation of ions at the surface of the electrode also depends on pore size of the electrode material. When the pore size of electrode material remains smaller than diameter of the hydrated ions, then ions will not be able to participate in double-layer formation. Electro-adsorption of the ions into different pore size materials not necessarily provides the same capacitance value even if they are of same surface area.

9.3.2 Pseudocapacitors

Although EDLC and pseudocapacitor coexist together in the supercapacitor device, for convenience these are explained separately for better understanding. In pseudocapacitor, charge stores in a Faradaic way, which allows the charges to pass across the double layer as batteries. However, capacitance arises because of the passing of charges across the interface, Δq , and potential change, ΔV . Hence, the derivative, dq/dV , is equivalent to capacitance [15]. There are many charge storage mechanisms for pseudocapacitor like adsorption pseudocapacitance, redox pseudocapacitance and intercalation pseudocapacitance as demonstrated in Fig. 9.3. In adsorption pseudocapacitance, electrolyte ions adsorb and desorb on the surface of the electrode material. Redox pseudocapacitance originates from fast reversible Faradaic reactions by electro-adsorption or intercalation of electrolyte ions on the surface of electrode. In intercalation pseudocapacitance, electrolyte ions intercalate on the van der Waals gaps or lattice of redox-active electrode materials [16, 17]. Although pseudocapacitive electrode material also takes place in the redox reaction shown ever, it is different

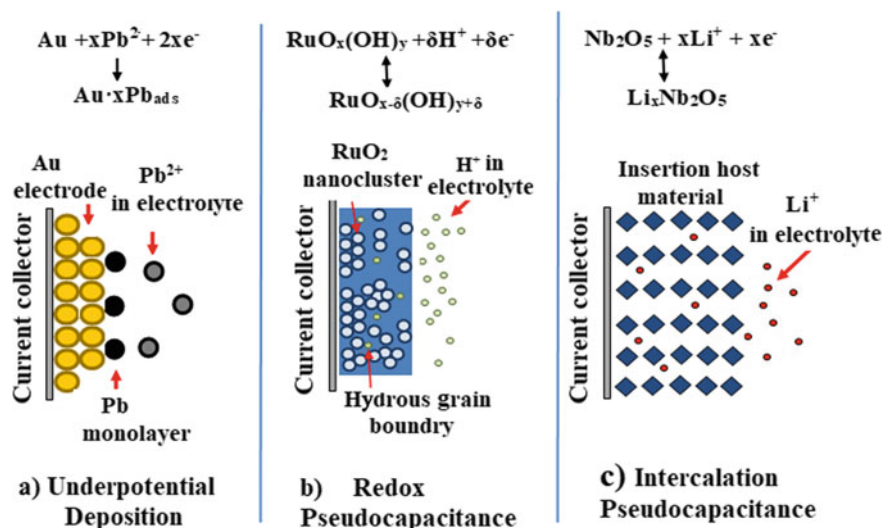


Fig. 9.3 Charge storage mechanisms in pseudocapacitor. Redrawn and reprinted with permission from [5]

from battery-type electrode material. Some examples of commonly used pseudocapacitive electrode materials are metal oxides (RuO_2 , MnO_2 , Fe_3O_4 , Fe_2O_4 , PbO_2 , MoO_3), metal hydroxides ($Ni(OH)_2$) and conducting polymers (PANI and PPY) [4].

9.3.3 Hybrid Capacitors

Hybrid capacitors come into the existence because of provisions of selection of different types of electrode materials in the same device. There are some confusions in the hybrid and asymmetric capacitor. In asymmetric capacitor, both electrode materials will be capacitive in nature but of different behaviors like one will be EDLC-type electrode material made of carbon-based materials and others are based on pseudocapacitive electrode materials like metal oxides, metal hydroxides and conducting polymers, while in hybrid capacitor one electrode material is of capacitive nature and other made of battery-type material. The goal behind the development of hybrid capacitor is to increase the energy density. In a symmetric capacitor, there is a problem of low potential window in the aqueous media because of gas evolution reactions and electrochemical oxidation of the electrode materials at high potential [16]. In the place of positive electrode, any Faradaic material with high oxygen evolution reaction over potential, e.g., Pb/PbO_2 and $Ni(OH)_2$, may be used. Positive redox electrode and negative carbon electrode can operate in the complementary electrochemical window [16]. This increases not only potential window and energy density but also the capacitance of the cell because of the presence of pseudocapacitive

electrode materials. Low self-discharge, high reliability, high operating temperature, high potential window and high energy density are the main advantages of the hybrid electrochemical capacitors.

9.4 Characteristics of Electrode Materials Used in Supercapacitors

Supercapacitor has four major elements/components, e.g., current collector, electrode, electrolyte and separator. Its performance depends on the materials used in all these four elements. The contribution of electrode and electrolyte remains high in deciding the performance (capacitance and energy density). The requirement of the electrode is high electrical conductivity. It should have a large surface area and mesoporous structure. The EDLC electrode does not undergo any chemical change during storing the charges, whereas electrodes used in pseudocapacitors are electroactive in nature and take part in Faradaic reactions. Also, electrodes in EDLCs are rigid; however, conducting polymer-based electrodes are much flexible.

For maintaining higher performance of SCs, proper selection of electrode materials is of uttermost importance. The performance of both types of SCs, EDLC and pseudocapacitors depends on the electrode material. The tuneable features of electrode can be achieved by using advanced materials, which show different properties from the bulk materials. By using nanoscience and nanotechnology, various interesting phenomena can be used for designing the materials suitable for electrodes. Since nanomaterial has a high strength-to-weight ratio and high surface area-to-volume ratio, they exhibit various attractive properties such as high conductivity, large surface area, good temperature stability and high corrosion resistance. The porosity of electrode can also be modified by using nanostructured materials. By using large surface area materials like carbon nanomaterial, the electrode-specific capacitance can be enhanced. Other important issues for electrode materials are the safety concern. The electrodes of SCs are safer to use for a long period, whereas are major safety issues are arising with batteries. Depending on the utility of the materials in different types of SCs, the materials can be classified as EDLC electrode material, pseudocapacitance electrode material and hybrid electrode material as demonstrated in Fig. 9.4. EDLC electrode materials are based on carbon materials. On the other hand, pseudocapacitor materials are composed of transition metal oxides (TMOs) and conducting polymers (CPs). The hybrid capacitors are made of carbon material, pseudocapacitor electrode material and battery electrode materials in combination.

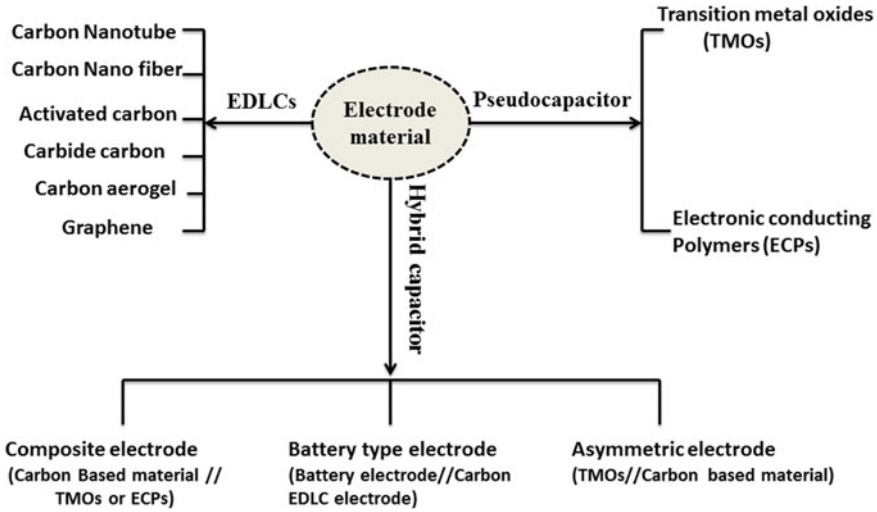


Fig. 9.4 Various electrode materials used in SCs

9.4.1 Electrodes for Supercapacitors

Electrode material is responsible for charge storage and capacitance of the supercapacitor device. Design of electrode material, which has a high specific surface area, high electrical conductivity, high chemical stability, lightweight, high thermal stability, corrosion resistance and low manufacturing cost, is the utmost goal for supercapacitor devices. Instead of high surface area, nanostructured pore size plays an important role in achieving high capacitance. An effective surface area is an important parameter for the high capacitance of supercapacitor. In the electrode material, all pores do not take part in charge storage. If the ion size is bigger than the pore size, ions will not accumulate on the surface of the pore; hence, those pore areas will be ineffective. Generally, pore size on the electrode surface should be double of the ion sizes to allow the effective coverage of the pore walls [18]. Pore size should be of around 0.7 nm for high capacitance, and as the pore size increases or decreases over or below 0.7 nm, capacitance starts decreasing [19]. Hence, pore size and pore distributions are the important criteria for the high capacitance of the SC devices. In Fig. 9.5, the specific capacitance of supercapacitor using different electrode materials like carbons for EDLC, and polymers and metal oxides for pseudocapacitor has been demonstrated. The last column demonstrates electrode materials for asymmetric and hybrid capacitors [20, 21].

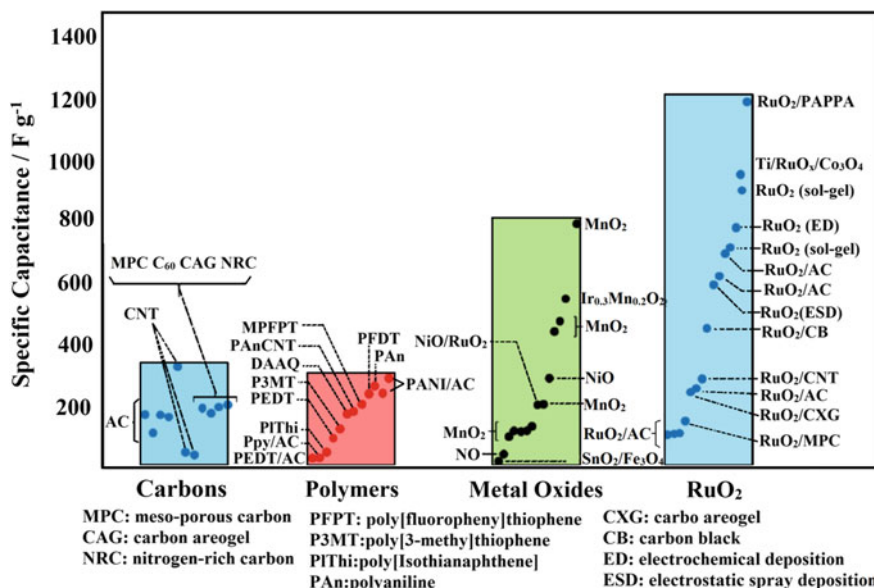


Fig. 9.5 Specific capacitance of supercapacitor using different electrode materials. Reprinted with permission from [22]

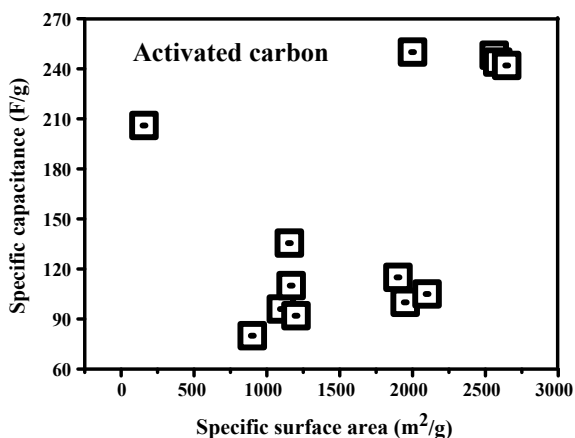
9.4.1.1 Emerging Materials: Carbon-Based Materials

Carbon exists in many allotropes like graphite, diamond, fullerene, graphene, carbon nanotube, amorphous carbon, etc. Among these allotropes, graphite, carbon nanotubes and graphene are good conductors of the electricity, which is an important parameter to serve as effective supercapacitor electrode material. Carbon has high conductivity and high chemical stability and is cheap and easily available, and it can achieve a high surface area, which makes it a suitable material to be used as electrode material for supercapacitors [23]. Carbon materials are used for EDLCs because they accumulate charge on the surface of the electrode material. High surface area, desirable pore size, pore size distribution and the presence of functional groups like oxygen, nitrogen and sulfur (responsible for pseudocapacitance) complement capacitance of the device. Commonly used carbon allotropes used as electrode materials are graphite, graphene, carbon nanotube, activated carbon and carbon areogel [13, 24].

Activated carbon

Activated carbon is mostly used carbon for supercapacitor electrode material because of high electrical conductivity, easy availability and moderate cost. It is derived from carbonaceous materials like waste biomasses (e.g., rice husk, human hair, coconut shell, etc.), coal and wood [13]. Activation of the carbonaceous material is performed via chemical or physical activation processes. Physical activation occurs in two steps,

Fig. 9.6 Specific capacitance versus specific surface area of activated carbons used for the electrode. Figure is drawn using the data of [26] and Table 9.2 of this chapter



first pyrolysis at 400–900 °C and then partial gasification at 350–1000 °C using an oxidizing gas (e.g., O₂, CO₂, steam and their mixture) [25]. Chemical activation is done by pyrolysis at 440–900 °C using chemical activators (e.g., KOH, NaOH, H₃PO₄, ZnCl₂, etc.) [25]. Activation process evolves different pore sizes, which are distributed over the surface. Pore size distribution shows the presence of micropores (<2 nm), mesopores (2–50 nm) and macropores (>50 nm). Micropores evolve inside the mesopores and mesopores inside the macropores, respectively. It is assumed that capacitance is linearly dependent on the specific surface area of the electrode material. Figure 9.6 demonstrates the relation between BET surface area and specific capacitance, which is contradicting the relation between specific surface area and specific capacitance though it depends on scan rate, current density, pore size of electrodes, pore size distribution of electrodes, etc. [26, 27]. An exclusive overview of the characteristics of activated carbon has been given in Chap. 4.

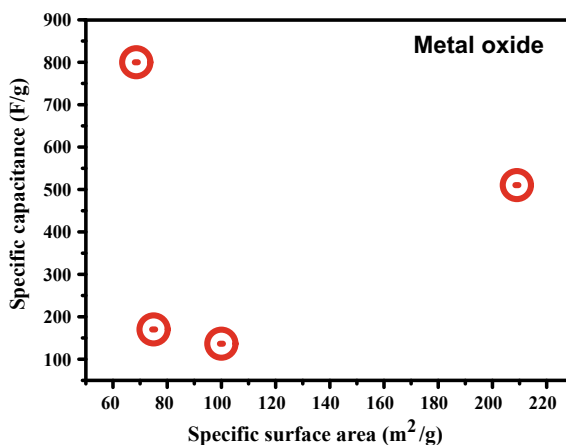
Graphene

Graphene is the two-dimensional single layer of carbon. It has high electrical conductivity, excellent chemical stability, high surface area and lightweight. It is independent of the pore size distribution of the solid electrode. Many methods have been developed for graphene productions such as chemical vapor deposition, micromechanical exfoliation, arc discharge method, unzipping of the carbon nanotubes, epitaxial growth, and electrochemical and chemical method. An exclusive overview of the characteristics of graphene has been given in Chap. 5.

Carbon nanotubes

CNT is a single-atom graphite sheet, which curls into a cylindrical form. CNTs have high electrical conductivity (10⁵ S cm⁻¹), high mechanical strength, high surface area, high flexibility and high chemical and thermal stability [13]. CNT is categorized into single-walled carbon nanotube (SWCNT) and multiwalled carbon nanotube (MWCNT). SWCNT and MWCNT both forms are used as supercapacitor electrode

Fig. 9.7 Specific capacitance versus specific surface area of metal oxides used for the electrode. Figure is drawn using the data of Table 9.2 of this chapter



material application. An exclusive overview of the characteristics of CNT has been given in Chap. 6.

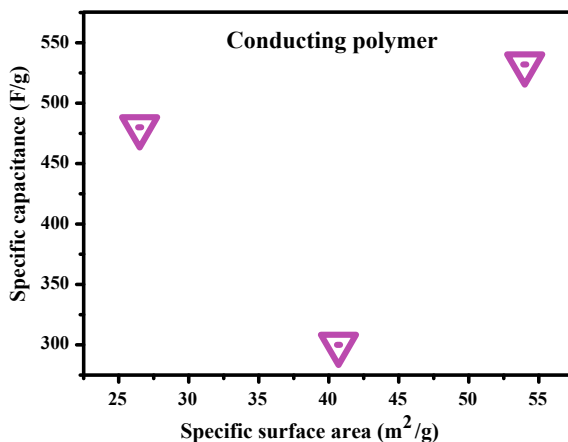
9.4.1.2 Emerging Materials: Metal Oxides

Transition metal oxides are also used as electrode materials because of high surface area, high ionic conductivity and mesoporous structure, which make them an effective electrode material for charge storage application. Metal oxides are used for pseudocapacitor, where fast Faradaic reaction takes place on the surface of the electrode material. Some commonly used metal oxide-based electrode materials are ruthenium oxide (RuO_2), manganese dioxide (MnO_2), nickel oxide (NiO), cobalt oxide (Co_2O_3), iridium oxide (IrO_2), iron oxide (Fe_2O_3), vanadium oxide (V_2O_5), indium oxide (In_2O_3) and tin oxide (SnO_2) [13]. Figure 9.7 demonstrates the relation between BET surface area and specific capacitance, which is again contradicting the relation between specific surface area and specific capacitance though it depends on several parameters like scan rate, current density, pore size of electrodes, pore size distribution of electrodes, etc. An exclusive overview of the characteristics of metal oxide has been given in Chap. 3.

9.4.1.3 Emerging Materials: Conducting Polymers

Conducting polymer is widely studied in the field of supercapacitors from the last two decades because of high energy density compared to metal oxides, low cost, easy to fabricate and low equivalent series resistance [13]. Conducting polymers are used for pseudocapacitors and store charges by redox reactions. Oxidation induces doping of electrolyte ions in polymer matrix, while reduction leads to de-doping of ions from the polymer matrix [23]. Examples of some commonly used conducting polymers

Fig. 9.8 Specific capacitance versus specific surface area of conducting polymers used for the electrode. Figure is drawn using the data of Table 9.2 of this chapter



for supercapacitor electrode materials are polyaniline (PANI), polypyrrole (PPY), polythiophenes, etc. [13]. Figure 9.8 demonstrates the relation between BET surface area and specific capacitance, which is also contradicting the relation between specific surface area and specific capacitance though it depends on various parameters like scan rate, current density, pore size of electrodes, pore size distribution of electrodes, etc. An exclusive overview of the characteristics of conducting polymers has been given in Chap. 8.

9.4.1.4 Emerging Materials: Special Types

Metal–organic frameworks

Metal–organic frameworks (MOFs), subclass of coordination polymers, are a class of compounds consisting of metal ions or clusters coordinated to organic ligands to form one-, two- or three-dimensional structures. MOFs have received attention in the field of the supercapacitors because of highly porous and molecular-level tunable frameworks. These are lightweight and of high surface area, high pore volume and controllable pore size structures. It is built by coordination bond formation resulting from weak interactions like van der Waals forces, hydrogen bonding, P-P stacking between organic and inorganic groups. MOF allows arranging single atomic active metal, which increases the interaction between electrode and electrolyte. It is the combination of inorganic node, which creates a corner of the framework, and these nodes get connected by the organic linker. Pore size of MOFs can be controlled in the range of 0.6–2 nm and can also incorporate pseudocapacitive electrode material within the framework, which extends its suitability as electrode material for supercapacitor devices. Low electronic conductivity is a big drawback of most of the MOFs. Composite of MOFs with carbon material is a solution to overcome this issue. Carbon materials, e.g., CNTs, rGO, etc., help to improve the electronic conductivity [18].

Covalent organic framework

Covalent organic frameworks (COFs) are linked by strong covalent bonds. These are two-dimensional and three-dimensional organic solids. The basic structure of COFs is similar to MOFs. They have a high surface area, controllable pore size and high flexibility. But instead of inorganic node and organic linkers, the framework is composed by lightweight elements like carbon, boron, oxygen with covalent bonds (B–O, C–N, B–N). COFs are light in weight, and now some of them are chemically and thermally more stable than MOFs [18].

MXenes

MXenes are a few atomic layer thick material composed of transition metal carbide, nitride and carbonitride (Nb_2C , Ti_3C_2) leading to the formation of two-dimensional structure. It consists of $M_{n+1}X_n$, where M represents transition metal and X is related to nitrogen and carbon with X (1, 2, 3, 4, 5 ...) [18]. MXenes have high electronic conductivity, good mechanical strength and hydrophilicity that establish them as a suitable material for supercapacitor energy storage applications.

Metal nitrides

Metal nitrides are gaining attention in the energy storage applications because of high electronic conductivity. A variety of metal nitrides are involved in the supercapacitor applications like molybdenum nitride (MoN), titanium nitride (TiN), vanadium nitride (VN), niobium nitride (NbN), ruthenium nitride (RuN), chromium nitride (CrN), which not only serve as the electrode material but also work as the mechanical backbone [28, 29].

Black phosphorus

Black phosphorus has got interest in energy storage application because of its 2D puckered structure with high surface area and electronic mobility with strong mechanical strength. Black phosphorus contains semi-connected nanosheets, which provide an open structure in the sponge [18].

9.4.2 Characteristics of Electrode Materials

Electrode accumulates and intercalates the electrolyte ions on its surface during charging and transfers electrical current to the current collector at the time of discharge. Electrode material is responsible to get high specific capacitance and to decide the potential window of supercapacitor device. As the charge storage capacity of the electrode increases, capacitance of the device also improves. Effective surface area of the electrode material influences the charge storage capacity of the device. The following are the characteristics of suitable electrode material (Table 9.1). Selected characteristics of a few electrode materials are given in Table 9.2. Figure 9.9

Table 9.1 Characteristics of electrode material for electrochemical supercapacitors

Primary characteristics	Secondary characteristics	Tertiary characteristics
High specific surface area	High chemical stability	Low cost
High electrical conductivity	Wide working temperature range	Non-toxicity
High charge storage capacity	High thermal conductivity	Easy to fabricate
Lightweight	High corrosion resistance	Easy availability
	Controllable pore size	

demonstrates the relation between BET surface area and specific capacitance, which is contradicting the relation between specific surface area and specific capacitance. Note that capacitance depends on scan rate, current density, pore size of electrodes, etc. It is desirable to have a high surface area.

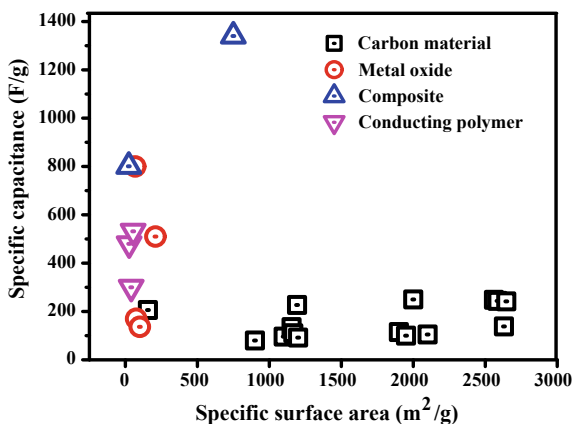
9.5 Concluding Remarks

Selection of appropriate material is a critical task for the fabrication of any high-performance device. A supercapacitor is composed of four essential counterparts, e.g., current collector, electrode, electrolyte and separator. The overall performance of the device depends on the properties of the individual component. Electrode material is used for the accumulation of ions on the surface of the electrode material during charging and vice versa. The main characteristics of an electrode material are highly effective specific surface area, extraordinary electrical conductivity, lightweight, chemical and thermal stability and cost-effective. According to the common requirements of electrode material, graphene, carbon nanotube, ruthenium oxide, activated carbon, nickel oxide, polypyrrole, manganese dioxide, polyaniline, etc., are found to be the most appropriate electrode materials to be used for the fabrication of high-performance supercapacitor devices.

Table 9.2 Properties of different electrode materials for supercapacitor performance

Electrode material		Specific surface area (m ² /g)	Density (kg/m ³)	Specific capacitance (F/g)	Electrolyte	References	
Carbon materials	Activated carbon	Shrimp shell	2000–2100	206 F/g at 0.1 A/g	6M KOH	[30]	
		Rice straw		242 F/g at 0.5 A/g	6M KOH	[31]	
		Oily sludge		248.1 F/g at 0.5 A/g	6M KOH	[32]	
		Coconut shell		250 F/g	1M H ₂ SO ₄	[33]	
		Citrus peel		110 F/g at 0.1 A/g	1M NaClO ₄	[34]	
		Sunflower seed		244 F/g at 0.25 A/g	6M KOH	[35]	
		Rotten carrot		1154.9	135.5 F/g at 2.2 A/g	6M KOH	[36]
		Graphene		2630	138 F/g at 10 A/g	Aqueous electrolyte	[37, 38]
Metal oxide	CNT	380–2005	1600	227 F/g at 5 A/g	H ₂ SO ₄	[39]	
	Ruthenium oxide (RuO ₂)	68.6	6970	800 F/g at 1 A/g	1M H ₂ SO ₄	[40]	
	Manganese dioxide (MnO ₂)	80–120	7200	72–201 F/g	Aqueous electrolyte	–	
	Nickel oxide (NiO)	153.2–265	6810	138.6–982 F/g at 1 A/g	6M KOH	[41]	
	Iron oxides	75	5250	170 F/g at 2 mV/s	1M Na ₂ SO ₄	[42]	
		750	–	1340 F/g at 25 mV/s	0.1M H ₂ SO ₄	[43]	
Composite	RuO ₂ /CNT	–	–	910 F/g at 10 mV/s	1M LiClO ₄ /PC	[44]	
	V ₂ O ₅ -XH ₂ O/CNT	23.3	–	801 F/g at 1 A/g	3M KOH	[45, 46]	
	NiO–Co ₃ O ₄	–	–	626 F/g at 2 A/g	1M H ₂ SO ₄	[47]	
Conducting polymer	Polyaniline (PANI)/α MnO ₂	30.9–77.1	1245	532 F/g at 1.5 A/g	1M H ₂ SO ₄	[48, 49]	
	Polyaniline (PANI)	26.5	1480	480 F/g at 10 mV/s	1M KCl	[50, 51]	
	Polypyrrole (PPY)	40.7	1400	300 F/g at 5 mV/s	0.1M LiClO ₄ /PC	[52, 53]	
	Polythiophenes (PTH)	–	–	–	–	–	

Fig. 9.9 Specific capacitance versus specific surface area used for the electrode. Figure is drawn using the data of [26] and Table 9.2 of this chapter



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