Copper oxide-based high-performance symmetric flexible supercapacitor: potentiodynamic deposition

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ABSTRACT

Flexible supercapacitors have gained significant attention in recent times due to their many advantages such as high specific capacitance, lightweight, long lifespan, high energy density, high flexibility, and high-power density. These benefits make them ideal for various high-power applications in various industries. Copper oxide is particularly attractive as an electrode material because of its high theoretical specific capacitance, low cost, and eco-friendliness. Copper oxide is the most promising electrode material in energy storage systems among metal oxides due to its higher theoretical value of specific capacitance (1800 F/g). In the present study, the synthesis of a thin film of copper oxide on a flexible copper substrate through electrodeposition was carried out to produce a flexible and lightweight supercapacitor. The supercapacitor's performance was evaluated using cyclic voltammetry (CV) and galvanostatic charge–discharge analysis in a 1 M KOH electrolyte. The results showed that the copper oxide/copper-based supercapacitor had a large specific capacitance of 983.3 F/g and good performance even after 2200 cycles, with a capacity retention of 89.70%. The flexibility of the electrode was measured at various bending angles. The electrode showed a capacity retention of 87.5% after a 180° bending angle with a good coulombic efficiency of 79.15%. Hence, it could be a promising material for flexible supercapacitor electrodes. This demonstrates that copper oxide has great potential as a material for flexible supercapacitor electrodes. The newer applications for supercapacitors in

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industries such as wearable electronics, flexible displays, and energy harvesting systems can be explored.

1 Introduction

In today's world, there is a growing demand for high-performance energy storage devices, and power sources have drawn a lot of interest because of their remarkable properties and unique characteristics to strengthen the performance of electronic devices [1]. It has become necessary for many electronic devices including the latest technology electric hybrid vehicles. The fast-growing world needs lightweight, integrated, and flexible electronic devices such as smartwatches, biomedical devices, e-newspapers, flexible touchscreens and displays, smart sensors, and actuators for portable electronic applications [2–5]. Supercapacitors made of solid-state materials that offer flexibility have become increasingly appealing in comparison to conventional capacitors, as well as batteries such as LIBs and SIBs. This is due to their ability to be lightweight, mechanically flexible, and offer high-power density and energy density, all while maintaining long life cycles [6]. The energy and power densities depend on three parameters of supercapacitors, namely specific capacitance (Cs), potential window range (v), and internal resistance of the electrode material. Supercapacitors are made up of two electrodes separated by an ion-transport layer in an aqueous solution, metal foils as current collectors, and an outer shell. Flexible supercapacitors consist of highly flexible and conducting carbon networks that work as both current collectors and electrodes [7, 8]. Based on their charge storage mechanism, flexible supercapacitors are divided into three categories namely electric double-layer capacitors (EDLC), pseudocapacitors (PCs), and hybrid capacitors [9, 10]. When it comes to storing electrical charges, there are two types of capacitors: EDLCs and pseudocapacitors. EDLCs use a nonfaradaic mechanism, meaning they store charge electrostatically without any chemical reactions occurring. They are typically composed of carbon-based materials like carbon nanotubes, activated carbon, and graphene. On the other hand, pseudocapacitors utilize a faradaic electrostatic process, which involves reversible redox reactions. These capacitors are commonly made of conductive polymers and transition metal oxides (TMOs) [11, 12]. Pseudocapacitors show a large specific capacitance along with a high energy density as compared with EDLCs because of the quick and reverse redox reaction. For this reason, several studies have been conducted on pseudocapacitive electrode materials for application in flexible supercapacitors. The behavior of a flexible supercapacitor is evaluated by the combination of energy and power densities, areal capacitance, and stability. To enhance the supercapacitive performance, TMOs have attracted lots of interest because of their higher conductivity, large surface area, and higher specific capacitance [13–15]. Among various TMOs, RuOx has been extensively investigated material for pseudocapacitors based on its high reversible redox reaction, higher conductivity, large potential window, large specific capacitance, better life cycle, better thermal stability, and high rate efficiency. However, it has some drawbacks such as not being eco-friendly and higher costs [16]. Therefore, researchers have focused on an alternative approach for finding low-cost and environmentally friendly electrode materials that show better electrochemical performance. MnO_2, V_2O_5, IrO_2, NiO, $NiOH_2$, Co_3O_4, Fe_3O_4, and CuO are some of these alternative electrode materials.

CuO has attractive features such as easy preparation, nontoxicity, low cost, and fascinating electric, optical, and electrochemical properties. These characteristics have led to research interest in CuO as an electrode for supercapacitors. CuO can deliver a higher theoretical value of specific capacitance up to 1800 F/g [17, 18]. Senthil Kumar et al. [19] have developed CuO with three different morphologies via a simple chemical deposition technique. Binder-free nanoplates of CuO electrode showed a higher capacitance of 536 F/g, while binders including film flower and bud-shaped CuO show a capacitance of 296 F/g and 230 F/g, respectively. Similarly, Zhang et al. [20] have deposited CuO with three morphologies, i.e., nanobelt, feather, and cauliflower-like shapes, using a simple chemical technique. The cauliflower-like CuO showed a high capacitance of 116.9 F/g with good reversibility compared to the other two shaped CuO samples. The nanostructured

copper oxide was prepared using a solution route on Cu foil as a substrate and showed a capacitance of 158 F/g in a 1 M Na_2SO_4 electrolyte [21]. Nanostructured CuO has been prepared via mechanochemical techniques with various morphologies, including nanoparticles, nanorods, and nanowires. CuO nanoparticles show a remarkable capacitance value of 113.5 F/g in 6 M KOH electrolyte [22]. Dubal et al. [23] have deposited CuO with different structures, such as stacked nanosheets, woollen clumps, and nanobuds, by using chemical bath deposition. The highest specific capacitance was discovered to be 396 F/g for the CuO nanobud-type electrode. Wang et. al., have found a remarkable capacitance of 569 F/g in a NaOH aqueous solution [24]. The method for the preparation of the electrode is one of the most important factors that led to a high surface area [50]. CuO has been deposited via different techniques including chemical bath deposition, ultrasonic, hydrothermal, sol–gel, and oxidation methods. Table 1 summarizes previously reported work on CuO electrodes for supercapacitors via different techniques.

To deposit thin films, electrochemical deposition is a more effective method, as it results in uniform deposition on a conducting substrate [26]. Electrodeposition is a method where a few parameters, such as the crystallographic orientation, thickness, and surface morphology of thin films, could be controlled by varying the voltage/current, temperature and deposition time, concentration, and pH of the solution.

Hence, homogenous thin films can be produced on conducting substrates with different shapes and areas via an electrochemical deposition method, which is not possible by other deposition techniques [11, 27, 28]. Lamberti et al. [25] fabricated a flexible and lightweight CuO electrode via an oxidation technique that exhibits a specific capacitance of 61.2 F/g. Very few works have been reported on CuO-based pseudo supercapacitors essentially due to their low electric conductivity and unstable cyclic performance. It was found that the capacitance retention was poor due to the crystal structure of CuO[49]. To alleviate this problem, the aggregation or interconnected nanoparticles (NPs) morphology of the active material may help. For commercial applications, CuO must overcome difficulties to (a) improve the value of the Cs closest to the theoretical value, (b) increase the energy and power densities, and (c) have a long life cycle. In practical applications, supercapacitors with high capacitance retention are important because they can provide reliable and consistent energy storage for a variety of applications, such as in electric vehicles, renewable energy systems, and other high-power applications. Additionally, high capacitance retention allows for longer device lifetimes and reduces the need for frequent maintenance or replacement, making supercapacitors a more cost-effective solution for energy storage.

Herein, we present an effective, simple, inexpensive, and eco-friendly strategy to deposit CuO thin films for symmetric flexible supercapacitors using flexible copper foil as a substrate. The novelty of this work lies in the development of a simple and eco-friendly method for depositing CuO thin films on flexible copper foil substrates, which can be used to fabricate flexible and lightweight electrodes for symmetric supercapacitors. We successfully synthesized a flexible and lightweight CuO electrode via the potentiodynamic electrochemical deposition method at ambient temperature from 1 M NaOH as the precursor solution. Our research aims to examine the super capacitive performance of a symmetric supercapacitor. In addition, the flexibility and stability of the electrode in an aqueous solution of 1 M KOH as an electrolyte were also examined. The advantages of using a KOH electrolyte are its lower resistance and higher ionic concentration as compared with other electrolytes such as Na_2SO_4 and NaOH. Overall, this

Table 1 Previously reported CuO electrodes for supercapacitors via different techniques

Sr. No	Method	Electrolyte	Specific capacitance (F/g)	Ref
1	Simple chemical precipitation	6 M KOH	133.6	[30]
2	Oxidation	Na_2SO_4	190	[45]
3	Chemical bath deposition	1 M Na_2SO_4	411	[31]
4	Electrospinning process	KOH	620	[46]
5	Chemical deposition	6 M KOH	115.3	[20]
6	Wet chemical	6 M KOH	88.5	[48]

study provides a new and efficient approach for developing flexible and lightweight supercapacitors with high electrochemical performance.

2 Materials and methods

2.1 Synthesis of CuO thin film

The chemicals used in the experiment were of high-quality analytical reagent grade and were used as received without any additional purification. A 1 cm × 1 cm flexible copper foil was used as the substrate for the electrodeposition of the CuO thin film. The surface of the copper foil was prepared by polishing it with Silicon Carbide paper, degreasing it with ethanol and acetone, and then cleaning it with double distilled water in an ultrasonication bath for 10 min. The resulting surface was smooth and bright in color. The electrodeposition was carried out in a 1 M NaOH solution at room temperature using a three-electrode electrochemical workstation (Metrohm AUTOLAB PGSTAT302 N). The flexible copper foil served as the working electrode and a platinum wire (Pt) was used as the counter electrode, while a saturated Ag/AgCl electrode in saturated KCl was used as the reference electrode. The deposition process was carried out using potentiostatic mode (cyclic voltammetry) by performing several cycles in different potential ranges at scan rates of 20, 50, and 100 mV/s. The potential window was varied from − 2 V to 2 V, − 1 V to 1 V, 0 V to 1 V, and 0 V to 2 V for each scan rate. The best results were obtained after 90 cycles at a 100 mV/s scan rate in a potential window from − 1 V to 1 V, as shown in Fig. 1, resulting in a smooth and uniform thin film with a blackish color.

The film was then rinsed with double distilled water and air-dried. The weight of the deposited CuO material was determined by weighing the substrate before and after deposition using a microbalance and was found to be 0.32 mg/cm^2.

2.2 Characterization

The structural and surface properties of the thin film were further analyzed using x-ray diffraction (XRD) and scanning electron microscopy (SEM) techniques. The XRD analysis was performed with CuKα radiation (λ = 0.1506 nm) to determine the crystal
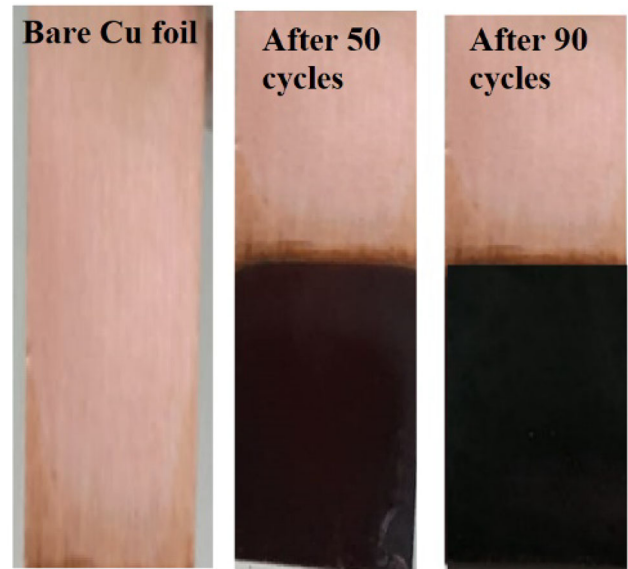

Fig. 1 Electrode deposition of CuO thin film

structure of the deposited material. The SEM was used to observe the surface morphology and study the distribution of particles on the surface of the film. To evaluate the electrochemical performance of the prepared electrode, cyclic voltammetry (CV) and galvanostatic charge–discharge (GCD) tests were conducted using a Metrohm AUTOLAB PGSTAT302 N potentiostat.

The tests were performed in a three-electrode system, with the as-prepared electrode and a Pt wire serving as the working electrode and counter electrode, respectively, and Ag/AgCl (in saturated KCl) used as the reference electrode. The electrolyte used was a 1 M KOH solution. The CV tests were conducted at various scan rates, ranging from 5 mV/s to 100 mV/s, within a suitable potential window. The GCD test was performed at a constant current density of 1 mA/cm2. The stability of the electrode was determined by performing additional CV tests, and its mechanical flexibility was evaluated through manual bending analysis.

3 Results and discussion

Generally, copper oxide semiconductors with various oxidation states and different morphologies exist in three phases: tenorite (CuO), cuprous oxide (Cu$_2$O), and paramelaconite (Cu$_4$O$_3$) [29]. Figure 2 indicates the XRD analysis of the as-prepared CuO thin film.
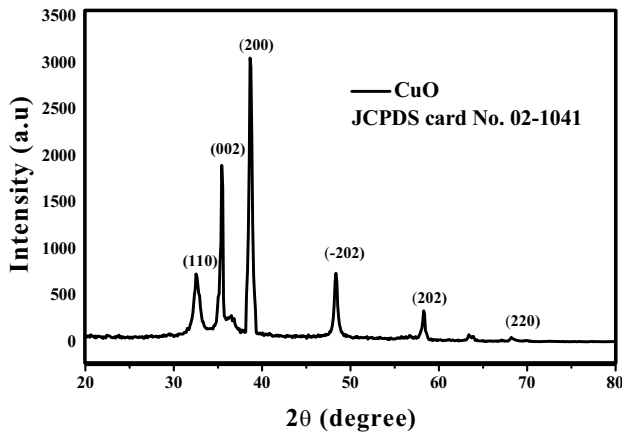
Fig. 2 XRD pattern of the as-prepared CuO thin film

Table 2 standard peak Vs observed peak for JCPDS #02–1041

Standard peaks	Observed peaks
32.49	32.51
35.52	35.53
38.95	38.93
48.81	48.80
58.29	58.27
68.13	68.19

All the peaks are well matched with the standard pattern of the monoclinic CuO tenorite (JCPDS #02–1041).]. The observed peaks compared with standard peaks are listed in Table 2. Other than this there is not a single peak found for impurities, indicating the formation of the pure CuO compound [30]. The width and intensities of the peaks indicate a highly crystalline nature, which suggests that the crystallography of the CuO thin films is not affected by the organic surfactants [19, 53]. The morphological study was examined via SEM images, as shown in Fig. 3. Figure 3a shows the bare micrograph of copper foil after the cleaning process. Figure 3b displays copper foil covered with interconnected nanoparticles (NPs) of spherical shape with random size. They are randomly distributed on the surface of copper foil with pores. The higher magnification image (Fig. 3c) shows that most of the NPs are agglomerated, while some are separated from each other. Figure 3 (d) shows a cross-section of NPs at higher magnification. The average size is less than 10 nm which provides a large surface area. This type of morphology is similar to the previous work, which increases

the surface area [28, 57]. Such type of surface morphology (porous and large surface area) is beneficial for the application of supercapacitors. Also, the agglomerated NPs lead to better cyclic stability [49]. Hence the stability issue of the electrode can be resolved by forming NPs.

The behavior of the as-prepared CuO electrode for supercapacitors was investigated by electrochemical analysis. The electrochemical analysis of the as-prepared CuO sample was conducted in 1 M potassium hydroxide (KOH) as an aqueous solution by using three-electrode cells. A deposited CuO sample was used as a working electrode wire was employed as the counter electrode and Ag/AgCl (in saturated KCl) was used as a reference electrode. KOH is a commonly used electrolyte in electrochemical devices such as batteries and supercapacitors. The advantages of using a KOH electrolyte compared to other organic electrolytes are its lower resistance and higher ionic concentration/conductivity [32]. The ionic conductivity of an electrolyte refers to its ability to conduct electric current through the movement of ions. In general, electrolytes with higher ionic conductivity allow for more efficient charge transfer, leading to better device performance. It was reviewed that the results are poor in Na_2SO_4 electrolytes as compared with KOH and H_2SO_4 electrolytes [50, 51, 58]. To activate the electrode material and to improve the contact with an electrolyte, the prepared CuO electrode was submerged in the electrolyte for 30 min, and then further CV cycles were carried out. Figure 4 shows the CV curve of thin film CuO at various scan rates of 5, 10, 20, 50, and 100 mV/s in the potential window range of − 0.1 V to 0.8 V at room temperature. The value of a specific capacitance was determined using Eq. (1) [33]:

$$Cs = \frac{1}{2mv(Vc - Va)} \int_{Va}^{Vc} I(V) \, dV, \tag{1}$$

where C represents the specific capacitance (F/g), Vc–Va is the voltage window range, v is the voltage scan rate (mV/s), I(V) represents the current density (mA/cm^2), and m is the mass of the active CuO material. The electrode at a scan rate of 20 mV/s exhibits the highest specific capacitance of 926.4 F/g. As observed in Fig. 4, the voltammetric current under the curve increased with an increasing scan rate. This behavior indicates that the voltammetry current is directly proportionate to the CV scan rate [34].

Fig. 3 SEM micrograph of **a** bare copper (**b–d**) as-prepared CuO
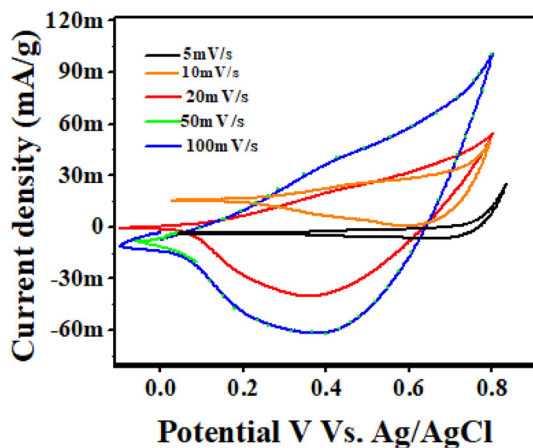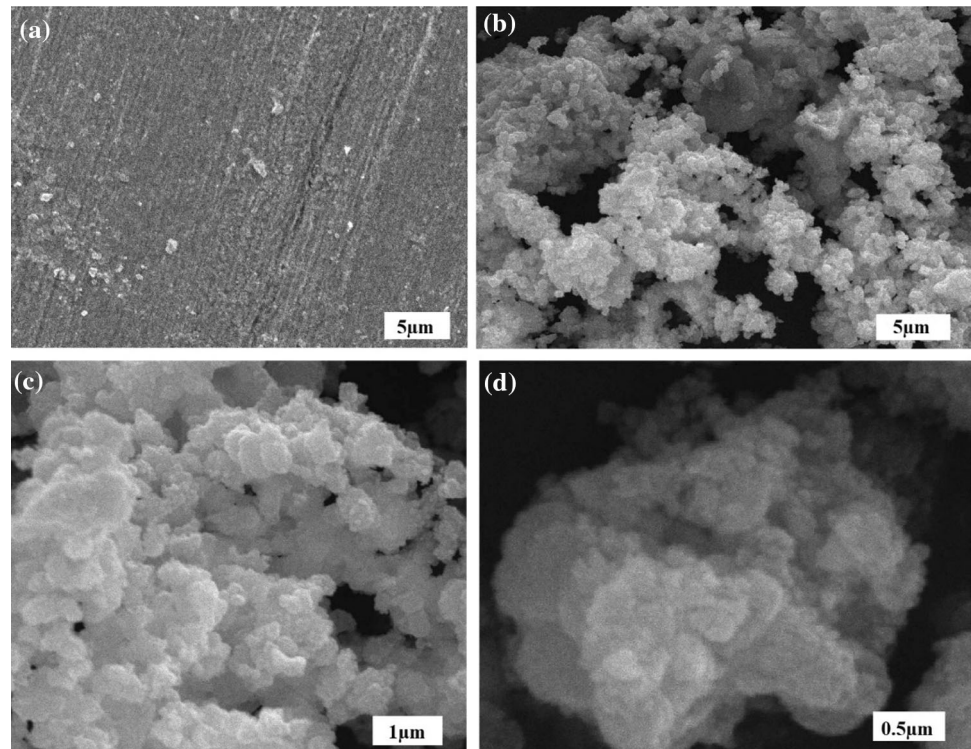

Fig. 4 CV curve of the prepared CuO electrode at different scan rates in a 1 M KOH electrolyte

A CuO/CuO-based symmetric pseudocapacitor was constructed by using prepared CuO electrodes as the anode and cathode schematic illustration shown in Fig. 5a. The electrochemical test was carried out in the same electrolyte of 1 M KOH aqueous solution. Figure 5b indicates the CV curve of the CuO/CuO-based symmetric supercapacitor in the voltage window range of − 0.1 V to 1.0 V at various scan rates of 5, 10, 20, 50, and 100 mV/s under room temperature. The maximum value of specific capacitance was found to be 983.3 F/g at 20 mV/s.

The values of specific capacitance for the CuO and CuO/CuO-based symmetric supercapacitors at different scan rates are listed in Table 3. In a symmetric supercapacitor, the electrolyte is generally chosen to have high ionic conductivity and low viscosity. This leads to a more effective charge transfer between the two electrodes, resulting in a higher specific capacitance for the supercapacitor compared to the individual electrode. In summary, it is concluded that the specific capacitance of an electrode may be less when used on its own compared to a symmetric supercapacitor formed by the same electrode, due to the more efficient utilization of the available surface area and the use of an optimized electrolyte for charge transfer.

It was observed that when the scan rate increased from 20 mV/s to 100 mV/s, the value of specific capacitance decreased, as summarized in Fig. 6. These results indicated that at a large scan rate, the inner active site is unable to undergo redox transitions. This might be caused by the diffusion effect between the ionic species of the electrolyte and the surface of the electrode [55, 56]. Hence for a higher scan rate, the value of specific capacitance is less.
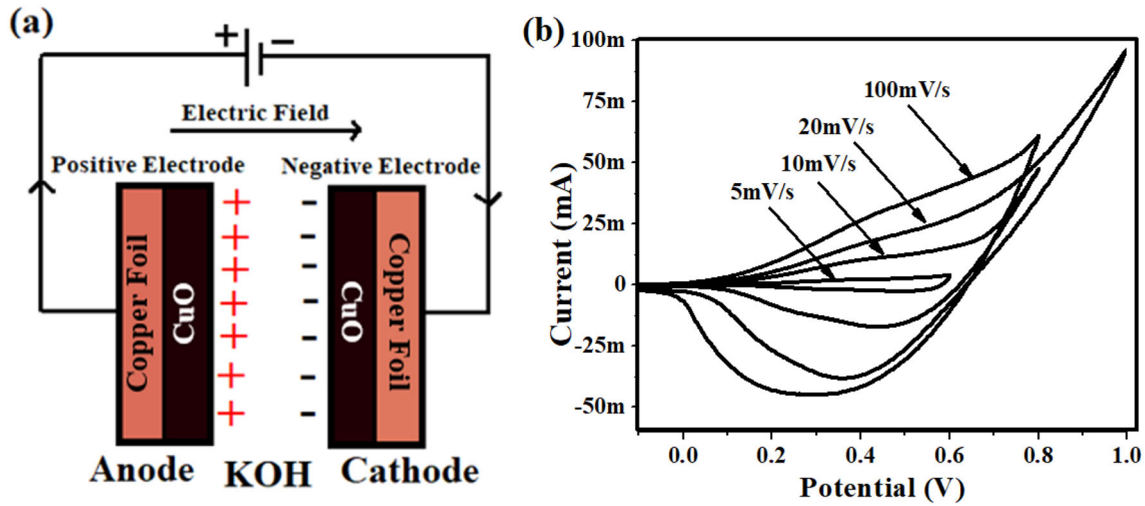
Fig. 5 **a** Schematic of the as-constructed symmetric supercapacitor. **b** CV curve of the CuO/CuO-based symmetric supercapacitor at various scan rates in a 1 M KOH electrolyte

Table 3 Specific capacitance for the CuO and CuO/CuO-based symmetric supercapacitors at various scan rates

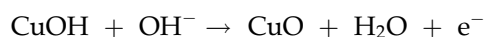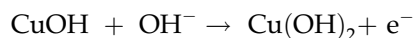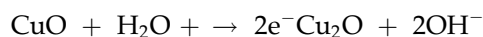| Scan rate (mV/s)	Specific capacitance (F/g)	
	CuO electrode	CuO/CuO-based symmetric capacitor
5	368.8	500
10	907.93	957.1
20	926.38	983.33
50	618.22	768.5
100	473.1	680.83
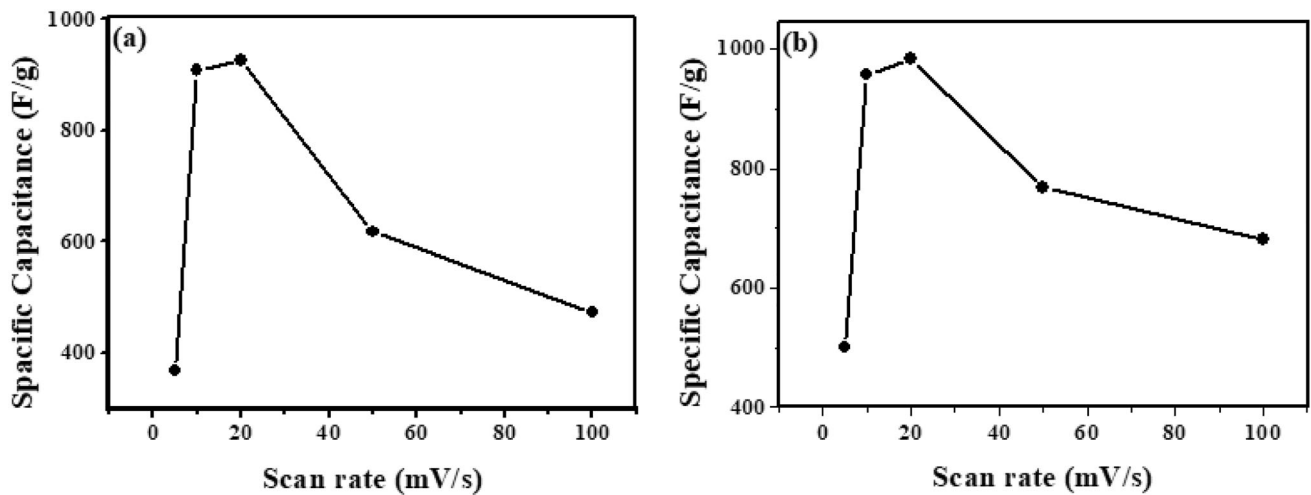
Fig. 6 Variation in the value of the specific capacitance at different CV measurement scan rates: **a** CuO electrode and **b** CuO/CuO-based symmetric SC

From Fig. 5b, it can be observed that the anodic peaks are not clear, while they are shifted toward the positive side with an increase in scan rate. With further expansion in the potential window range, the cathodic peak of the CV curve gets disturbed. This indicates that reversible electrochemical reactions can occur in the active electrode materials up to 1.0 V. As observed in Fig. 5b, the shape of the CV curves for

the CuO/CuO-based symmetric SC differs from those of the EDLCs, which is close to a rectangular cross-section shape, suggesting that charging–discharging of CuO material is controlled by the process of faradaic redox reactions [35]. It exhibits a maximum current area under a wide redox peak, implying the properties or behavior of faradaic pseudocapacitance [36]. The pseudocapacitance of TMO has been assigned to redox transitions of species at different states of oxidation [37]. Hence, according to the CV curve, the charging and discharging of the CuO/CuO-based symmetric SC in a KOH alkaline electrolyte in the voltage window range of -0.1 to 1.0 V can be summarized as follows: [35, 38].

$$CuO + H_2O + \rightarrow 2e^- Cu_2O + 2OH^-$$

$$Cu_2O + H_2O + 2OH^- \rightarrow 2Cu(OH)_2 + 2e^-$$

$$CuOH + OH^- \rightarrow Cu(OH)_2 + e^-$$

$$CuOH + OH^- \rightarrow CuO + H_2O + e^-$$

Moreover, the distinct anodic peaks may be due to the following factors: (a) in-complete transformation between Cu^+ and Cu^{2+}, (b) impact of water splitting, (c) overlapping oxidation reaction process from Cu_2O or/and CuOH to CuO or/and $Cu(OH)_2$, and (d) higher electric resistance of $Cu(OH)_2$ [39–41]. Table 4 represents a comparative study of our work and previously reported work on CuO thin films by using the electrochemical deposition technique.

To examine the stability of the CuO/CuO-based symmetric supercapacitor, a CV test was conducted for 2200 cycles in a 1 M KOH electrolyte at a 100 mV/s scan rate, as shown in Fig. 7. From the figure, it is clear that for the first 500 cycles, the current under the area decreases resulting in loss in the value of specific capacitance. This result indicates the film started degrading from 1st cycle to 500 CV cycles. Whereas between 500 and 2000 cycles, it became stable, hence no loss in the capacitance value from 500 to 2000 CV cycles. Even after 2200 cycles, the electrode exhibited less degradation, and the electrode shows good cyclic stability of 89.70% capacity retention after 2200 CV cycles.

Thus, the results demonstrated that the active electrode material was extremely stable during the CV test. After 2200 CV cycles, the fading of capacitance was ascribed to the loss of the active material [49]. The loss in the value of specific capacity is also owing to the nature of the active electrode material and the continuous process of oxidation/reduction reactions, as a result of which the volume of the active electrode material changes [19, 54].

Figure 8a–b indicates the Galvanostatic charge–discharge (GCD) plot of the as-prepared CuO electrode and CuO/CuO-based symmetric SC, respectively, in an electrolyte of 1 M KOH at a 1 mA/cm² constant current density. The GCD curve (Fig. 8a) was discovered to be asymmetric or nonlinear (quasi-

Table 4 Comparative study between the present work and previously reported work of CuO electrodes via the electrodeposition method

| Sr. No	Experimental Details			Electrolyte	Specific capacitance (F/g)	Ref
	Chemicals	Applied current/voltage	Deposition time and temp			
1	1 M NaOH	-1 V to 1 V at 100 mV/s	Room temperature	1 M KOH	983.3	Our work
2	0.5 M NiSO$_4$, 0.5 M NiCl$_2$, 0.01 M CuSO$_4$, 5% dimethyl sulfoxide and 1 M H$_3$BO$_3$, pH $\sim$ 3.8	-0.78 V	27 °C	3 M KOH	880	[49]
3	0.1 M copper sulfate + 0.1 M citric acid + 1 M NaOH, pH $\sim$ 10	0 to 1.1 V/SCE	Room temperature	1 M Na$_2$SO$_4$	179	[50]
4	0.05 M copper sulfate + 0.05 M citric acid + 1 M NaOH, pH 9	1.05 V/SCE	–	1 M Na$_2$SO$_4$	36	[51]
5	2 mol/dm³ KOH	20 mA/cm²	–	6 mol/dm³ KOH	212	[40]
6	–	-450 mV vs. Ag/AgCl	Room temp	1 M KOH	57.44	[52]
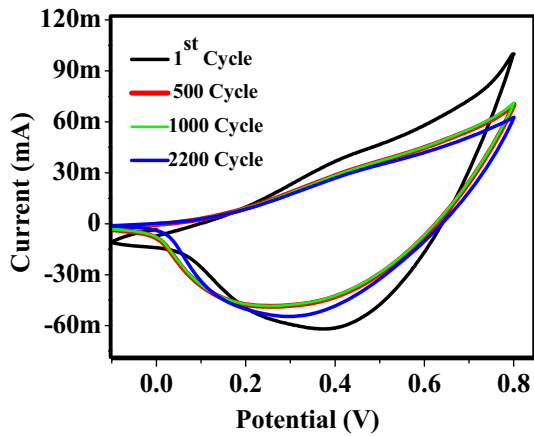
Fig. 7 CV curve of the CuO/CuO-based symmetric supercapacitor at a 100 mV/s scan rate for 2200 cycles in a 1 M KOH electrolyte

triangular). In the discharging process, there are three variations, as shown in Fig. 8c [42, 43].

The following observations are made (a) due to the internal resistance, there is an instant drop in current, (b) linear voltage variation with time shows double-layer capacitance behavior, and (c) the slope voltage variation with time shows pseudocapacitance behavior.

The GCD curves for the CuO/CuO-based symmetric SC (Fig. 8b) display an approximately triangular shape and a linear discharge curve, suggesting a typical capacitive nature and good electrochemical performance that might minimize the amount of energy lost during the fast faradaic reactions [35]. The value of the specific capacitance of an electrode can also be calculated from GCD via the following relation[11]:
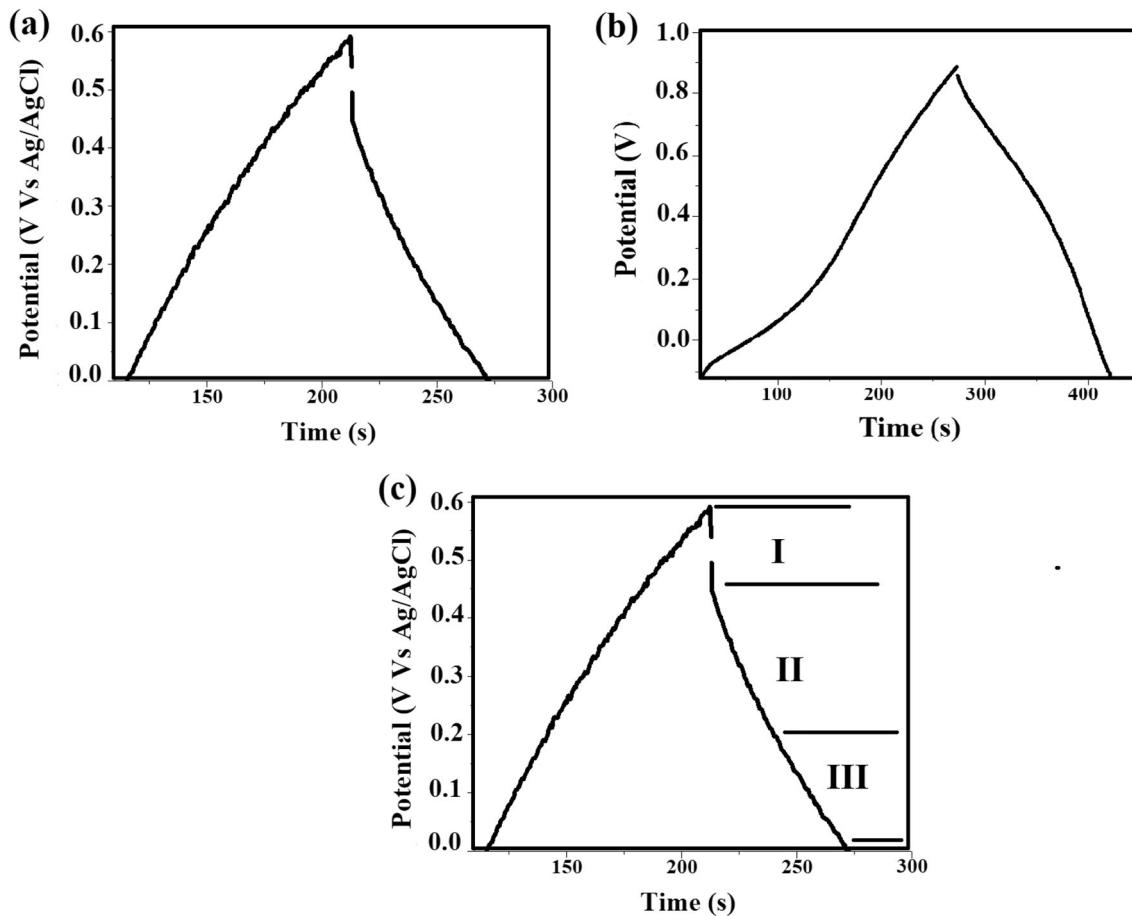

Fig. 8 Galvanostatic charge–discharge (GCD) curve in a 1 M KOH electrolyte at a constant current density of 1 mA/cm^2: **a** CuO electrode, **b** CuO/CuO-based symmetric SC, and **c** three variations in the discharging process

$$Cs = \frac{I \times \Delta t}{m \times \Delta V}$$

where I indicates the discharge current for the applied period Δt, m is the mass or weight of the deposited CuO, and ΔV denotes the potential window. The obtained maximum specific capacitance of 855 F/g and 896 F/g for the CuO electrode and symmetric CuO/CuO device from the discharge curve at 1 mA/cm^2 current density is much higher than the previously reported work in Ref [19, 20, 30, 31]. As a result, a symmetric CuO/CuO charge/discharge curve achieved a good coulombic efficiency of 79.15% at 1 mA/cm^2. The coulombic efficiency is calculated by the following relation:

$$\eta = \frac{t_d}{t_c} \times 100\%$$

where t_d represents discharge timing and t_c indicates charging time.

Electrodes for portable electronic devices should possess better mechanical flexibility [44, 47]. Along with better electric conductivity, high energy density, and long life cycles, flexible supercapacitors should possess unvarying performance under mechanical distortion at different bending angles. To evaluate the flexibility of the electrode, CV tests within the potential window range of − 0.1 to 1.0 were examined at various bending angles of 0°, 45°, 90°, and 180° at a 100 mV/s scan rate, as shown in Fig. 9. The bending analysis was carried out consecutively, and the angles were manually adjusted. It was observed that the CV curves for 0° and 45° are similar. However, there is an insignificant change in the CV curve for 90° and 180°, which shows remarkable capacity retention of 87.5% after the 180° bending angle, supporting the mechanical stability and flexibility of the electrode. Hence, the electrode could be used in flexible supercapacitors.

4 Conclusion

In conclusion, the study on copper oxide (CuO)-based high-performance energy storage by symmetric flexible supercapacitor with potentiodynamic deposition has shown that this material has great potential for use in energy storage devices. The method of potentiodynamic deposition results in a uniform and well-controlled deposition of CuO onto the current collector, leading to a high energy and power density in the final device. The flexibility of the current collector also makes the device well-suited for integration into flexible and wearable systems, providing a new level of versatility in energy storage. The results from the study show that the CuO electrode exhibits high specific capacitance, with a value of 926.4 F/g at a scan rate of 20 mV/s. This high value of specific capacitance can be attributed to the pseudocapacitive behavior of the CuO/CuO-based
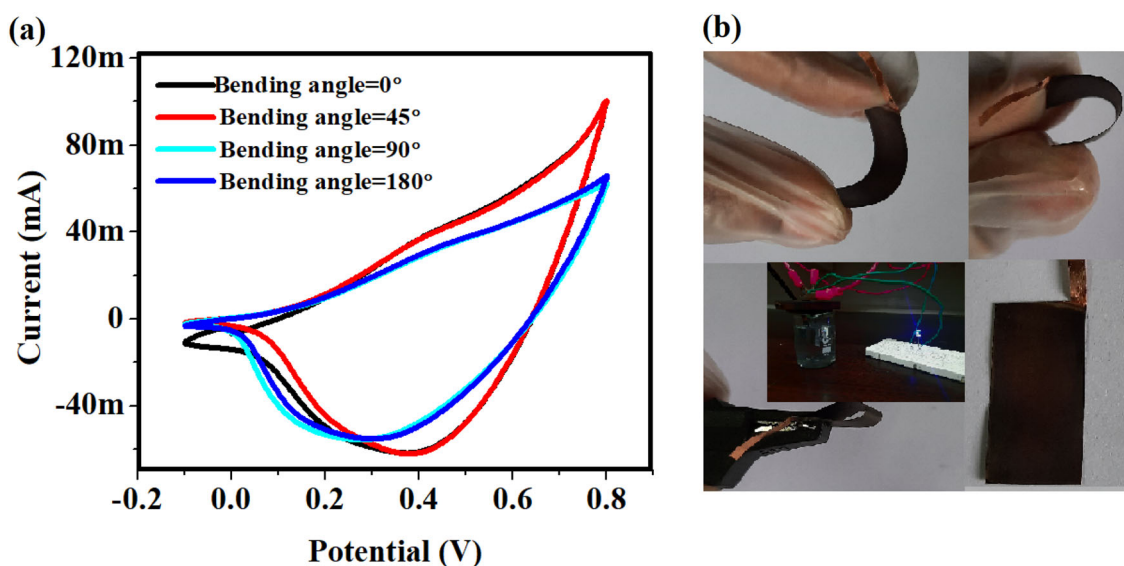

Fig. 9 a CV curves of CuO/CuO-based symmetric SC at different bent angles and **b** photograph of a bent electrode, inset: The demonstration of symmetric device to glow the LED

symmetric supercapacitor, which exhibited a specific capacitance of 983.3 F/g at the same scan rate.

The increase in the specific capacitance in the CuO/CuO-based symmetric supercapacitor compared to the single CuO electrode is due to the different capacitive behaviors of the two devices. The single CuO electrode showed three variations in the charge/discharge process, while the CuO/CuO-based symmetric supercapacitor exhibited pseudo-capacitive behavior. These results demonstrate the potential of CuO/CuO-based symmetric SCs as a material for high-performance energy storage in supercapacitors. However, it is important to note that further research is needed to understand the performance and stability of these devices, as well as to optimize the production process for mass production. Overall, the study highlights the importance of continued research in the area of high-performance energy storage, as new materials and methods are developed and evaluated. With advancements in energy storage technology, we can expect to see new and improved devices that will play a crucial role in enabling sustainable energy systems for the future.

Author contributions

Conceptualization: SS, AS and US, Formal analysis: AS, Investigation: SS and AS, Methodology: SS, AS, US, PH and NN, Project administration: US and NN; Resources: SS, Software: AS, US, and NN, Supervision: AS and US, Validation: PH and NN, Visualization: PH, Writing—original draft: SS, Writing—review and editing: AS, US, PH, and NN. All authors have read and agreed to the published version of the manuscript.

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Data availability

All data and material collected are presented in the manuscript. Clarification on any matter can be made through the corresponding author.

Declarations

Conflict of interest The authors declare no competing financial interest.

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