Journal of Energy Storage 134 (2025) 118229

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Review article

Flexible wireless charging energy storage devices☆

Yihang Cao [a], Yunshuo Zhang [a], Yuzhe Chen [a], Xuan Zhang [a], Ning Ding [a], Xiang Zou [a], Mingze Wang [a], Shujuan Liu [a], Weiwei Zhao [a,*], Qiang Zhao [a,b,*]

[a] State Key Laboratory of Flexible Electronics (LoFE), Institute of Advanced Materials (IAM), Nanjing University of Posts & Telecommunications, 9 Wenyuan Road, Nanjing 210023, China

[b] College of Electronic and Optical Engineering, College of Flexible Electronics (Future Technology), National and Local Joint Engineering Laboratory of RF Integration and Micro-Assembly Technology, Nanjing University of Posts & Telecommunications, Nanjing 210023, China

ARTICLE INFO

Keywords:
Flexible electronics
Wireless charging
Flexible supercapacitors
Integrated devices

ABSTRACT

With the rapid proliferation of flexible electronic devices, there is an increasing urgency for portable, lightweight, and intelligent charging solutions. Flexible wireless charging energy storage devices represent a cutting-edge technological breakthrough, which aims at providing more efficient and convenient charging and energy storage solutions for diverse devices without physical connections. This innovative approach primarily utilizes electromagnetic fields to supply energy in storage devices. First, this review comprehensively outlines various wireless charging technologies that is applicable to flexible supercapacitors (FSCs). Then, the review delves into the latest advancements in integrating wireless charging with FSCs and systematically analyzes these integrated devices from the perspectives of materials, manufacturing processes, and structural designs. Finally, this review elucidates the current challenges in this field and provides insights into the future prospects of wireless charging energy storage devices and their integration applications.

1. Introduction

With the rapid advancement of flexible electronics, a revolutionary transformation is reshaping the way of electronic devices [1,2]. Traditional rigid energy storage methods, such as conventional batteries and solid supercapacitors, have been proven unable to meet the needs of emerging applications such as next-generation wearable devices, flexible displays, and smart textiles [3,4]. These novel electronic products require energy storage and charging solutions with the advantages to achieve unprecedented flexibility, portability, and intelligence [5,6]. At present, portable, lightweight and smart charging solutions are not only crucial for the next-generation electronics, but also a key factor to drive the development of the entire industry [7]. Flexible wireless charging energy storage devices have emerged as a cutting-edge technological breakthrough. The design concept of these innovative devices aims to fundamentally change traditional charging and energy storage paradigms to offer a more efficient and convenient wireless charging and storage solutions for a variety of flexible electronic products. Their core principle is to use electromagnetic fields for energy transfer between devices, thereby eliminating the constraints of traditional charging cables and providing users with an entirely new experience.

At present, the researches on flexible wireless charging energy storage devices primarily focus on two interconnected yet challenging areas: the development of FSCs and the integration of wireless charging technologies [8,9]. FSCs have become a research hotspot in this field because of their unique advantages including high power density [10], quick charging-discharging rates [11], and excellent cyclic stability [12]. These characteristics make FSCs an ideal energy storage unit for flexible electronic devices. Concurrently, wireless charging technology is also undergoing rapid innovation [13]. From initial near-field magnetic induction charging to current far-field radio frequency charging, the technological advancements have enabled more flexible energy transmission and storage in space [14,15]. Among them, electromagnetic induction (EMI) charging is widely applied due to its simplicity and

☆ This review delves into various flexible wireless charging energy storage devices, covering their types, fundamental principles, and advancements. It details the integration of wireless charging with FSCs, exploring their properties, applications, and fabrication methods. The article concludes by examining the ongoing challenges and future directions in this field.

* Corresponding authors at: State Key Laboratory of Flexible Electronics (LoFE), Institute of Advanced Materials (IAM), Nanjing University of Posts & Telecommunications, 9 Wenyuan Road, Nanjing 210023, China.

E-mail addresses: iamwwzhao@njupt.edu.cn (W. Zhao), iamqzhao@njupt.edu.cn (Q. Zhao).

https://doi.org/10.1016/j.est.2025.118229
Received 11 January 2025; Received in revised form 3 April 2025; Accepted 25 August 2025
Available online 28 August 2025

reliability, but is limited by the transmission distance [16]. Magnetic coupling resonance (MCR) charging overcomes the distance limitation, but faces the problems of efficiency and interference [17]. Radio frequency (RF) charging can achieve long-distance transmission, but the power is low [18]. More importantly, effectively combining these two cutting-edge technologies still faces many challenges. For example, how to ensure the flexibility of FSCs while achieving efficient wireless charging and improved equipment integration is still a key scientific question at present.

With the advancement of wireless transmission and FSCs, charging methods are evolving towards wireless and intelligent systems, while FSCs are moving towards miniaturization and portability. The integration of these two technologies can lead to the development of more flexible and lightweight integrated devices (Fig. 1). This review aims to provide a comprehensive and in-depth perspective on the latest research progress in the field of flexible wireless charging energy storage devices. We will detail various wireless charging technologies for FSCs including EMI charging, MCR charging, and RF charging. First, it offers a detailed introduction of the different types of FSCs and wireless charging routes, and thoroughly discusses the cutting-edge advancements in integrating wireless charging integrated with FSCs. Then, the properties and applications of integrated devices are analyzed from the multiple aspects of materials science, fabrication technologies, and structural configurations. Finally, the current challenges and futural prospects in the field of wireless charging and energy storage integration, such as energy transfer efficiency, equipment stability, and mass production issues, are discussed.

2. Wireless charging principle

The wireless charging principle is fundamentally rooted in EMI, a concept pioneered by Nikola Tesla during his groundbreaking experiments on wireless power transmission in the 1890s [19]. Over the years, this technology has significantly matured and experienced rapid development and widespread applications in the field of electrical equipment [20] and wireless communications [21]. Wireless charging, also known as inductive charging, is a technology that allows energy transfer between a power source and an electronic device without physical connectors. This method utilizes electromagnetic fields to induce an electric current in the receiving device, enabling cordless power transmission [22]. Compared with the traditional wired charging method, the significance of wireless charging lies in its convenience, improved durability of charging ports, and potential seamless integration into various environments and applications. This revolutionary approach enables electronic devices to automatically receive charging energy within a designated area, offering a more efficient, convenient, and safer charging method.

2.1. Classification

Wireless charging systems can be broadly classified into three categories based on three technologies: inductive coupling, magnetic resonance coupling, and non-directional radio frequency (RF) radiation.

2.1.1. Inductive coupling

Inductive coupling typically refers to the phenomenon based on magnetic field induction, precisely Ampere's law and Faraday's law of induction [23]. When an alternating current flows through a primary coil, it generates a changing magnetic field and facilitates the transfer of electrical energy between two coils (Fig. 2a). This near-field magnetic power can induce a voltage suitable for charging wireless devices or storage systems. Inductive coupling usually operates within the kilohertz range. While the effective charging distance is generally within 20 cm, the charging power can be substantial reaching kilowatt levels in electric vehicle recharging applications [24].

The most notable features of inductive coupling include easy implementation, low cost, and high-power transmission exceeding kilowatt levels [25]. This technology has been widely applied in our daily life. For example, the inductively coupled chargers have been applied in mobile phones and other consumer electronics [26]. Electric vehicles, including plug-in hybrid electric vehicles, also require high-power charging, leading to the adoption of inductive coupling for this purpose [27,28]. Inductive coupling coils can be integrated into devices to transmit energy wirelessly, and can even be used to drive engines, achieving flexible and remotely controllable properties. For instance, Bandari et al. [29] have proposed a versatile microsystem designed for precise movement and operation, featuring a receiver coil integrated on the platform between two engines. This setup utilizes inductive coupling with an external transmitter to wirelessly transfer power and activate the device.

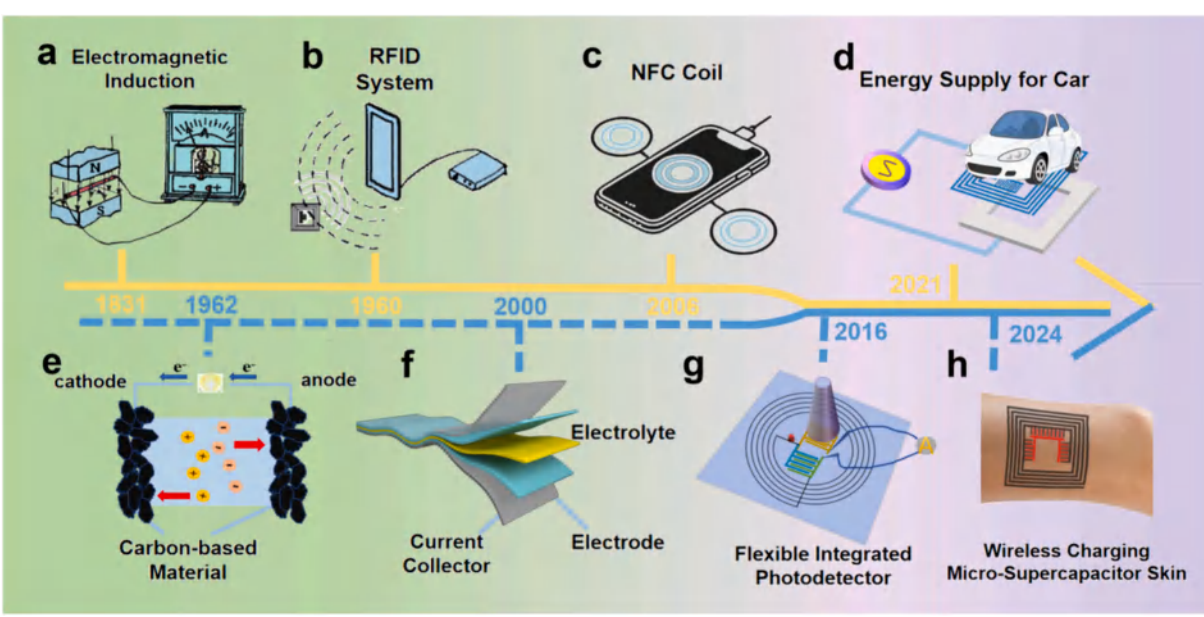

Fig. 1. The development of wireless transmission and supercapacitors and illustrations of integrated flexible devices for wireless charging and energy storage.

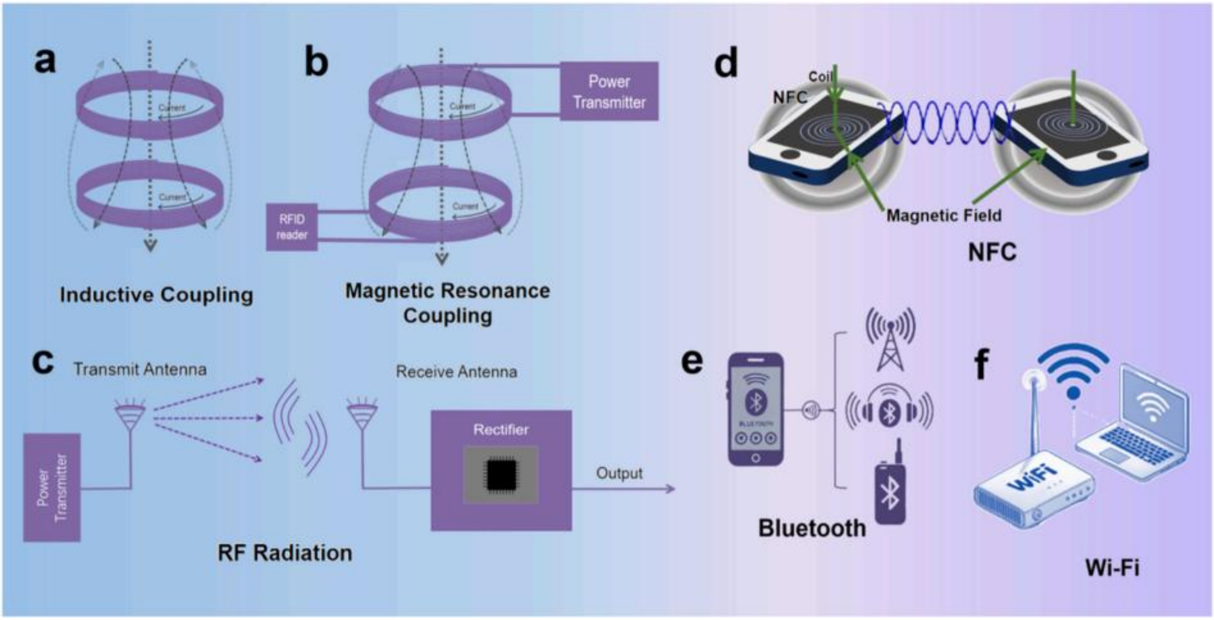

Fig. 2. Models of wireless charging systems. (a) Inductive coupling. (b) Magnetic resonance coupling. (c) Far-field wireless charging.

2.1.2. Magnetic resonance coupling

Magnetic resonance coupling involves the generation and transfer of electrical energy between two resonant coils through a dynamic or oscillating magnetic field (Fig. 2b) [30]. The coils are tuned to the same resonant frequency and thus resulting in efficient energy transfer and minimal energy leakage to the surroundings. This frequency tuning ensures optimal energy transfer while minimizing environmental losses. Notably, magnetic resonance coupling exhibits resilience to diverse environmental conditions. Unlike inductive coupling, it does not require a direct line of sight between the transmitter and receiver. This characteristic enables energy transfer across greater distances and through obstacles, which offers a significant advantage over traditional methods.

Magnetic resonance coupling, often referred to as strong coupling, presents a viable method for high-power charging. By modifying the turns ratio or adjusting the current magnitude, the operational power can be effectively regulated from several watts to tens of watts [17]. This technology finds applications predominantly within medical devices [31] and household items [32] due to its adaptable power range. The significant penetration capability of magnetic resonance coupling is exemplified by achieving over 60 % charging efficiency at a 20 cm distance, which uses a 3 cm transmitter coil paired with a 2 cm receiver coil [33]. This efficiency underscores the suitability of magnetic resonance coupling for smaller-sized implant devices and extended charging ranges. Additionally, electric vehicle charging systems that employ magnetic resonance coupling have been validated and assessed, which demonstrates their capacity for longer charging distances and enhanced charging efficiencies [34]. For example, Kurs et al. [35] have proved that the magnetic resonance coupling coils can extend transmission distances up to 8 times the radius of the coils. Moreover, this technology can transfer 60 watts of power over distances exceeding 2 m, and thus achieving over 40 % efficiency.

2.1.3. RF radiation

RF radiation involves using diffused radio frequencies or microwaves as a medium to carry radiant energy, typically within the frequency range of 300 MHz to 300 GHz [36]. It is mostly used for long-distance communications such as satellite communications [37] and wireless Internet [38]. The key components of an RF power harvesting system are the rectifying antennas of receivers. The basic principle of transmission is straightforward that alternating current is initially converted into direct current. This direct current is then transformed into RF by a magnetron and emitted by the transmitter. As it propagates through the air, the RF or microwave energy is captured by the rectifying antenna of the receivers, where it is converted back from RF to direct current to produce electrical energy (Fig. 2c). At the same time, RF radiation can propagate in all directions, and only one transmitting antenna is needed to transmit power to multiple receiving antennas. To achieve point-to-point transmission, forming energy beams can enhance transmission efficiency and directional clarity.

Microwave radiation, aside from its capability for long-distance transmission, is primarily characterized by its ability to simultaneously transmit energy and information, making it compatible with existing communication devices. This concept utilizes the modulation of information via microwave amplitude and phase, leveraging microwave radiation and oscillation for energy transmission. It is referred to as Simultaneous Wireless Information and Power Transfer (SWIPT) [39]. RF energy transmission and collection is a highly promising technology. By providing wireless power to devices within a Wi-Fi network, it can be used for self-sustaining Internet of Things (IoT) devices [40]. For example, Kudaibergenova et al. [41] have proposed sensors in IoT devices can achieve self-powering via RF energy transmission and harvesting within Wi-Fi networks, thereby eliminating the necessity for wired connections to power sources.

Inductive coupling enables efficient short-range power transfer (<1 coil diameter) through tight magnetic flux linkage but requires precise alignment [42]. It is commonly used in consumer electronics because of its low frequency (100 kHz-10 MHz) and high transmission efficiency [43]. Magnetic resonance coupling extends the operational range (1–10 coil diameters) via resonant frequency matching, tolerating moderate misalignment while maintaining mid-range efficiency [17]. Both of the aforementioned methods involve transferring power between two coupled coils. In contrast, RF radiation achieves long-distance transmission (>10 m) through propagating electromagnetic waves, but its efficiency is significantly reduced due to far-field attenuation effects [44]. These modalities represent a fundamental trade-off between transfer distance, efficiency, and alignment sensitivity, with inductive coupling dominating high-power proximity applications, resonant coupling bridging intermediate-range needs, and RF radiation serving low-power, omnidirectional scenarios.

2.2. Wireless transmission technology

Wireless transmission technology is now integrated into various aspects in our daily life with numerous transmission methods available, including radio frequency identification devices (RFID), near-field communication (NFC), Bluetooth, and Wi-Fi et al.

RFID is a non-contact automatic identification technology that facilitates data exchange via RF [45]. A key component of an RFID system is the electronic tag, which consists of a microchip and a coupling antenna for wireless communication (Fig. 1b). Once the input frequency of the electromagnetic wave matches the frequency within the antenna, identification is achieved. However, due to the constraints of its operating principle, the effective range of RFID technology is relatively short. RFID technology can be coupled with electronic devices for wireless transmission. For instance, Nesser et al. [46] employed a novel RFID technique connected to sensors to achieve wireless transmission of high-sensitivity strain measurement data , resulting in a wireless strain sensor with a gauge factor of 50 at 1 % strains. NFC, recognized as the most widely adopted RFID communication standard, has experienced rapid development in recent years (Fig. 2d) [47]. Data transmission between NFC devices occurs through magnetic or inductive coupling. When a reader is close to the NFC chip, it generates a magnetic field that induces a current to enable their magnetic coupling. Key advantages of NFC include its high security, fast speed, and convenient connectivity. However, its operational range is notably short, typically around 5 cm [48]. For example, Wang et al. [49] built a NFC-based localization system named Textile Sense, which enables ordinary surfaces to precisely locate objects in the near-field. Through experimental evaluations, this system has demonstrated an average accuracy of 3.5 cm when tracking the positions of objects within several tens of centimeters from the furniture.

Bluetooth is a new radio technology that transmits at 2.4 GHz and is a straightforward, user-friendly solution designed for connecting devices over short distances, characterized by its low cost, low power consumption, and high speed. (Fig. 2e) [50]. For example, Wallin et al. [51] conducted tests on Bluetooth's electromagnetic compatibility in a clinical setting, demonstrating that individual Bluetooth connections are robust and exhibit high compatibility. Wi-Fi is a wireless communication technology that employs RF signals for data collection and transmission [52]. Unlike Bluetooth, Wi-Fi offers significantly greater transmission distance and speed, making it primarily suitable for IoT services (Fig. 2f). For example, Mesquita et al. [53] characterized a novel Wi-Fi-enabled device, the ESP8266 module, which is integrated into IoT applications. This module is particularly suited for battery-powered IoT applications, with a transmission interval measured in seconds.

RFID/NFC systems represent the standard for secure proximity interactions, offering unparalleled advantages in passive power operation and contactless data exchange particularly valuable in payment systems, access control, and industrial automation where millimeter-level precision is required [54]. Bluetooth technologies, have emerged as the dominant solution for personal area network connectivity by achieving an optimal balance between power consumption and sufficient bandwidth for continuous biometric monitoring or audio streaming [55]. Wi-Fi is preferred for high-speed, infrastructure-dependent IoT applications and data-intensive tasks due to its ability to provide fast, reliable, and widespread connectivity, making it ideal for environments that require seamless data transfer and robust network support [56]. The following table compares four wireless technologies in terms of security, transmission distance, transmission speed, power consumption, and operating frequency (Table 1).

3. FSCs

3.1. Concept

FSCs are a popular type of energy storage device based on high-speed electrostatic or Faraday electrochemical processes with the advantages of superior safety, higher power density, faster charging-discharging rates and longer cycling life compared to batteries [62,63]. FSCs offer several advantages over traditional rigid supercapacitors, making them essential for the development of advanced electronic devices. Unlike conventional supercapacitors, which are limited by their rigid structure and are often confined to specific applications, FSCs can be integrated into a wide range of flexible, lightweight, and wearable devices [64]. These capacitors can be bent, stretched, and conform to irregular surfaces without compromising performance [65], which opens up new possibilities for applications in flexible electronics [66], wearable health monitors [11], and smart textiles [67]. Furthermore, their flexibility enables the creation of more compact and versatile energy storage solutions that are crucial for next-generation devices, such as flexible displays and energy-harvesting systems [68]. The development of FSCs is driven by the growing demand for portable, lightweight, and adaptable power sources that can meet the needs of modern, increasingly mobile and flexible technology. As a result, FSCs are expected to play a vital role in the advancement of sustainable and efficient energy storage solutions for a wide array of applications.

Essentially, FSCs consist of three main components: electrodes, electrolytes and current collectors. As a key component of FSCs, active materials are chosen for electrodes due to their exceptional properties including high conductivity, excellent charge-storage capability, large surface areas, and multiple active sites [69–71]. Electrode materials typically include metal-based materials [72] such as Ag [73] and Au [74], MXene-based materials [70,71] like Ti_3C_2 [75], and carbon-based materials [69] like graphene and carbon nanotubes. Electrolytes are selected based on criteria such as electrochemical stability, dielectric constant, accessible surface area, and a moderate voltage window [76]. They generally include aqueous [77], ionic liquids [78], solid-state or quasi-solid-state [79], as well as redox-active electrolytes [80]. Meanwhile, current collectors require materials with high conductivity, electrochemical stability, mechanical strength, and optimal density to ensure efficient performance [81]. For example, Zhao et al. [82] have prepared 2D $Cu_3(HHTP)_2$ conductive metal-organic frameworks (c-MOFs) films on indium tin oxide/polyethylene terephthalate(ITO/PET)

Table 1
Comparisons of different wireless technologies.

		Transmission Speed	Transmission Distance	Power Consumption	Operating Frequency	Reference
RFID	LF	1–10 kpbs	0–10 cm	Several μW (passive)	125–134 kHZ	[57,58]
	HF	10–424 kpbs	10 cm-1 m	High (others)	13.56 MHz	
NFC		106 kbps 212 kbps 424 kbps	0–20 cm	Low	13.56 MHz	[48,59]
Bluetooth		0–784 kpbs	0–60 m	Lower than NFC	2.4 GHz	[59,60]
Wi-Fi		11 Mbps- 54 Mbps	30–100 m 10–30 m	High	2.4 GHz 5 GHz	[60,61]

substrate by layer-by-layer assembly method, and then assembled them into high-performance symmetrical FSCs by polyvinyl alcohol (PVA)/KCl gel electrolyte, which exhibits a high specific areal capacitance of 939.2 μF cm^{-2}, with a capacitance retention of 85 % after 3000 cycles.

3.2. Classification

Depending on the charge storage mechanism, FSCs can generally be divided into three categories: electric double layer capacitors (EDLCs), pseudocapacitors (PCs), and hybrid capacitors (HSCs).

3.2.1. EDLCs

EDLCs is one of the simplest and most commercially available supercapacitors, where the essence of EDLCs is electrostatic attraction [83]. When the electrode comes into contact with an ion-conducting electrolyte, there is no charge transfer. Charges spontaneously form a double layer at the electrode-electrolyte interface without undergoing a Faradaic process, involving only the rearrangement of charges (Fig. 3a). As a result, the energy is stored by forming the electric double layer at the surface. The capacitance of an EDLCs electrode depends on the specific surface area of the electrode materials, which can be generally estimated according to formula 1 [63].

$$C = \frac{\mathcal{E}_r \mathcal{E}_0}{d} \cdot A \tag{1}$$

It is known that the capacitance (C) of an EDLC is directly proportional to the relative permittivity ($\mathcal{E}_r$) of the electrolyte, the vacuum permittivity ($\mathcal{E}_0$), and the effective surface area (A) of the electrode materials which can be accessed by electrolyte ions, and inversely proportional to the effective charge separation distance (d) between the double layers. Due to their ability to absorb and desorb conductive ions during charge and discharge processes without redox reactions, combined with a high specific surface area, porous carbon-based materials are often used as electrodes for EDLCs [84]. The double-layer characteristic can increase the effective surface area of the EDLCs by orders of magnitude. By employing a novel in-situ copper template method, Zhao et al. [85] have successfully synthesized 3D layered graphene carbon materials, which boast a large specific surface area, excellent electrical conductivity, and a layered open porous structure. They demonstrate outstanding EDLCs performance, achieving a power density of up to 1066.2 kW kg^{-1} in aqueous systems. However, due to the finite conductivity and unavailability of all the surface sites, commercial supercapacitors based on EDLCs electrode materials can only store energy in the range of 3–10 Wh kg^{-1} [63].

3.2.2. PCs

The essence of PCs lies in Faradaic reactions, which involves oxidation-reduction reactions on the electrode surface or ionic insertion reactions (Fig. 3b) [86]. There are three types of PCs including underpotential deposition, redox PCs, and intercalation PCs. The difference lies in the mechanisms: underpotential deposition occurs due to the potential difference created by absorbed ions and cations, redox PCs depend on the thermodynamics of redox reactions, and intercalation PCs involve the adsorption and insertion of ions into redox-active materials. A common characteristic of these three types is that most ions undergo rapid and reversible charge transfer on the surface of the active material, which causes changes in the valence state of electrode materials, with most redox sites located at the interface between the electrode and the electrolyte (Fig. 3d). The capacitance arises from the linear relationship between the charge range (ΔQ) and the potential change (ΔU). Therefore, the performance of PCs depends on the charge transfer during the redox process and the changes in the oxidation states of the electrode materials. The unique characteristics of PCs result in a substantial potential difference between the electrode and electrolyte surfaces, leading to stored charges that are several orders of magnitude greater than those achieved through conventional EDLCs processes. From a mechanical standpoint, a key criterion in distinguishing EDLCs from PCs lies in the occurrence of Faradaic reactions. It is whether the cation inserts into the hydrated layer and retains a hydrated shell. For example, Wu et al. [87] have synthesized $CuCo_2S_4$ nanowires on carbon paper and utilized them

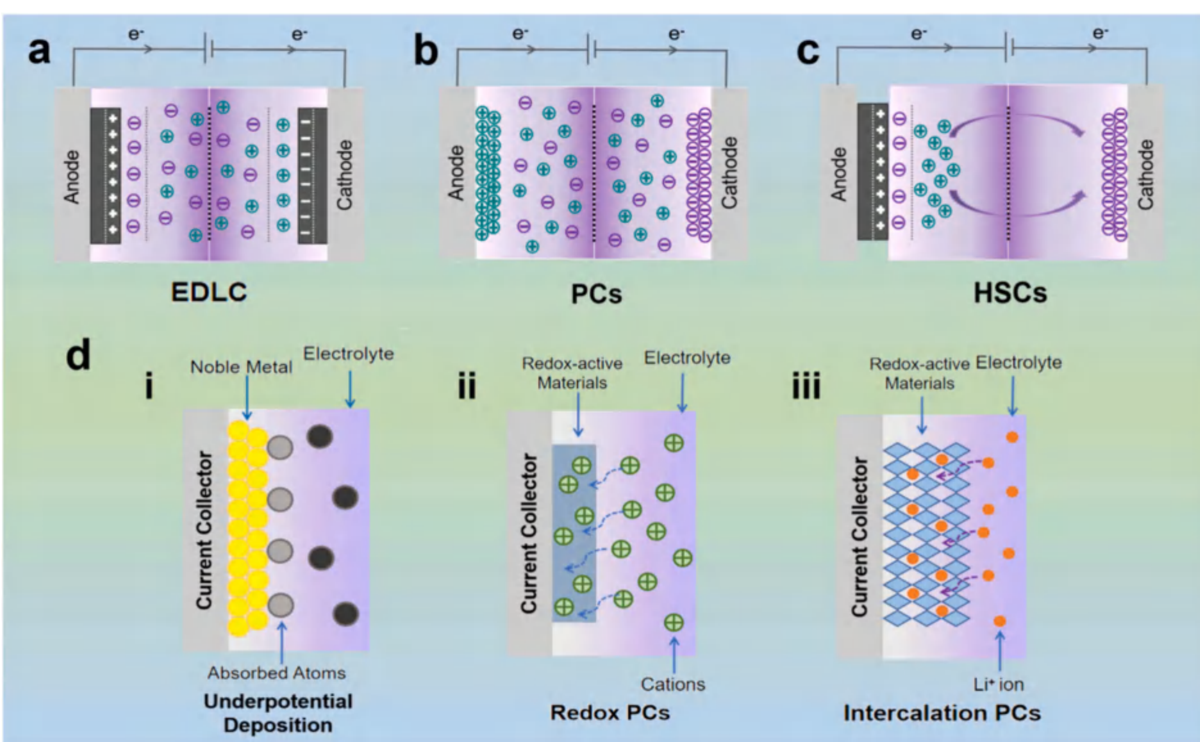

Fig. 3. Schematic illustration of supercapacitors. (a) EDLCs. (b) PCs. (c) HSCs. (d) Different types of pseudocapacitive electrodes: (i) underpotential deposition, (ii) redox PCs, and (iii) ion intercalation PCs.

as the positive electrode in asymmetric aqueous supercapacitors (AASCs). The activated carbon (AC) serves as the negative electrode. By combining the pseudocapacitive characteristics of $CuCo_2S_4$, the energy density of the PCs reaches up to 74.17 Wh kg^{-1}.

3.2.3. HSCs

HSCs are usually coupled in the way that the two electrodes have different charge storage mechanisms: one capacitive and one Faradaic [88]. Therefore, its storage principle is the combination of EDLCs and PCs (Fig. 3c). Electrodes with two different mechanisms exhibit different potential differences, which supports the capability of HSCs to achieve higher energy and power densities, and thus enhancing their overall voltage output [89]. Currently, charging methods for supercapacitors primarily involve constant current charging, constant voltage charging, and pulse charging [90,91]. For example, Xie et al. [92] have developed a 3D interdigitated structure for a flexible zinc-ion hybrid capacitor (ZIHC), which incorporates a hydrogel containing Zn^{2+} as the electrolyte and integrated with $Ti_3C_2T_x$-MXene electrodes. Notably, $Ti_3C_2T_x$ exhibits mechanisms of both EDLCs and PCs, and thus making it suitable for hybrid capacitors. The 3D interdigitated electrodes are fully encapsulated by the ion-conductive hydrogel and demonstrate a high areal capacitance of 1432 mF cm^{-2} and an energy density of 389.7 μWh cm^{-2}.

FSCs with different energy storage mechanisms including EDLCs, PCs and HSCs exhibit distinct application profiles due to their fundamentally different charge storage mechanisms and electrochemical characteristics. EDLCs, which rely on electrostatic charge separation at the electrode-electrolyte interface, demonstrate exceptional power density and ultrafast charge and discharge capabilities [93]. These properties make them particularly suitable for applications requiring instantaneous power delivery, such as meeting peak power demands in real-time motion monitoring systems [94]. PCs utilize faradaic redox reactions at the electrode surface to achieve substantially higher energy density, albeit with moderately slower charge transfer kinetics. This performance profile renders them ideal for continuous health monitoring devices that require sustained operation between charging cycles [95]. HSCs synergistically combine both charge storage mechanisms, offering an optimized balance between energy and power density, suitable for applications that need to balance fast charge and discharge and long running, such as wearable devices [65]. To sum up, the application difference of FSCs stems from the balance of energy, power and life of their energy storage mechanism, and the optimal type should be selected according to the requirements of specific scenarios.

4. Integrated wireless charging flexible energy storage device

4.1. Structure and property

The seamless integration of multiple devices without the hassle of external connections has sparked a growing interest in combining wireless charging with flexible energy storage solutions. In general, a typical wireless charging system consists of a transmitter and a receiver [96]. FSCs can be typically connected in series or parallel to increase their output voltage or current [97], and by integrating the receiving coil with the capacitor, an integrated device can be obtained [98]. This design enhances the convenience and compactness of the device, making it highly suitable for various electronic applications where space and performance are critical. The aim is to create compact solutions that provide both charging capabilities and energy storage within the same device supply. Wireless charging can eliminate the external cumbersome circuit by replacing the traditional external power, thus enhancing convenience, portability, and usability in various applications, ranging from implanted electronics to consumer electronics and beyond [99,100].

The compactness of integrated devices depends on the structural of the devices, which serves as a key factor limiting performance aspects such as charging, discharging, and transmission. For instance, Liu et al. [101] simply connected two supercapacitors in series on the same substrate, employing screen-printing technology to apply silver paste onto ethylene-vinyl acetate copolymer (Fig. 4a). Both supercapacitors are symmetric, with one electrode composed of polypyrrole nanoarrays and the other of 3D carbon nanoarrays. This setup enables charging through inductive coupling with an output voltage exceeding 2 V, making it a fundamental wireless charging supercapacitor. This study explores the integration of energy storage devices using wireless charging technology for portable, waterproof, and outdoor applications. However, this approach may reduce the transmission efficiency.

By changing the structural design of the supercapacitor and the coil, the energy loss can be reduced and the device integration can be enhanced. The design of shared electrodes can increase the transmission efficiency to a certain extent. For instance, Wang et al. [97] have developed an integrated wireless charging energy storage system including a wireless charging coil and monolithically integrated micro-supercapacitors. The coil is in the center surrounded by 60 MSCs with a shared single electrode, achieving seamless connection through lithographic patterning (Fig. 4b). It consists of two series-connected MSCs arranged in 30 rows side by side. Compared with a single capacitor, this design doubles the output voltage and increases the output capacitance by 15 times, demonstrating excellent series-parallel characteristics. By connecting the other interface of the coil and applying a 10 V DC current to the transmitting coil, a 5.4 V voltage can be generated in the receiving coil for charging with only one interface of the shared electrode to be fixed. After disconnecting the transmitting coil, the other electrode of the MSCs connected can discharge. The MIMSCs can output a voltage of 3 V and a current exceeding 5 μA for 30 min (Fig. 4c-d).

Integrating multiple device structures on a single plane can improve space utilization, and at the same time, the voltage window and the energy density can be increased through the selection of materials [104]. For example, Yue et al. [103] have integrated a power receive, an asymmetric MSC, and a photodetector of perovskite NWs on a single plane substrate. The power receive is the wireless charging coil mentioned earlier. In creating this device, a base layer of Au is first deposited onto the substrate, serving as the electrode foundation. Next, MnO_2-polypyrrole and V_2O_5-polianiline composites are applied to the positive and negative electrodes, respectively, due to their beneficial electrochemical properties. The device uses a gel electrolyte made from PVA and lithium chloride (LiCl), enhancing ionic conductivity and stability (Fig. 4e). In this flexible microcircuit device system on a polyimide substrate, a circular charging coil is positioned externally. It seamlessly connects to the electrodes of both the MSC and the centrally integrated photodetector (Fig. 4f). The device demonstrates a substantial operational range with a potential window of 1.6 V. It achieves a maximum energy density of 19.81 mWh cm^{-3} at a power density of 0.32 W cm^{-3}, and a peak power density of 2.57 W cm^{-3} at an energy density of 14.64 mWh cm^{-3}.

Using higher-performance flexible materials can effectively enhance the energy density of capacitors, while more compact designs of coils and capacitors can significantly improve transmission efficiency. In modern integrated systems, the pursuit of miniaturization, compactness, and high performance has become a prevalent trend. For example, Gao et al. [105] have pioneered the integration of wireless charging with MSCs in a device known as integrated wireless charging micro-supercapacitors (IWC-MSCs). This device consists of two main components: the MSCs and the wireless charging chip (WCC), which also serves as an antenna. To better seamless integrate the MSCs and WCC, Gao et al. have proposed an innovative structure, which is called planar coaxial structure. In this structure, the MSCs are centrally positioned, encircled by a coil that not only connects the MSCs and WCC but also serves as a shared electrode for three parallel interdigital MSCs. The coil in the IWC-MSCs is created by lengthening one electrode within the MSCs to serve as the antenna for wireless charging (Fig. 5a-(i). Both components are crafted from activated carbon combined with PVDF, Ketjen Black, and *N*-methylpyrrolidone to create an electrode slurry.

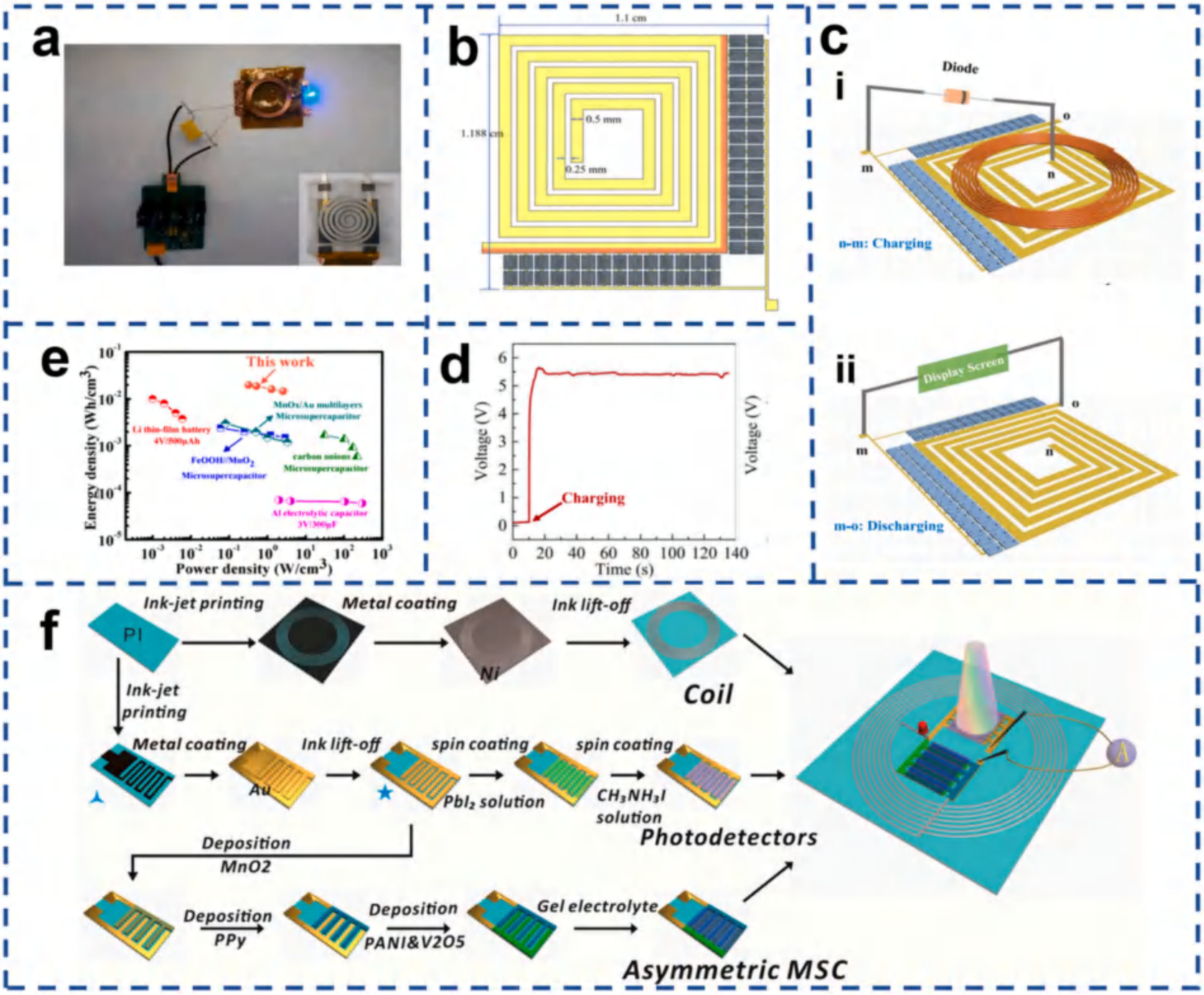

Fig. 4. (a) Practical test chart for supercapacitors adopted from [101]. b) A dimensional diagram of seamlessly integrated wireless charging MIMSCs microcell adopted from [102]. c) (i) Schematic diagram of charging. (ii) Schematic diagram of discharging. d) Charging curve of MIMSCs charged by a wireless coil. e) Schematic illustrating the fabrication process of all-solid-state flexible asymmetric MSCs. f) Ragone plots of MnO_2-PPy//V_2O_5-PANI asymmetric MSCs compared with other energy storage devices adopted from [103].

This mixture is then applied to graphite paper and formed into the device through a one-step laser etching process (Fig. 5a-(ii)). In the structural design, the different number of layers and the number of electrodes will also have an impact on the overall performance (Fig. 5b). A standout feature is its ability to bestow MSCs with wireless charging capabilities using magnetic fields, thereby substantially reducing connection distances between different components. The IWC-MSCs showcase in this study stand out with their ultra-high areal capacitance, reaching an impressive 454.1 μWh cm^{-2}, alongside an energy density that peaks at 463.1 μWh cm^{-2} (Fig. 5c). The devices also achieve a wireless transmission efficiency of 52.8 %. This seamless integration of cutting-edge technologies marks a significant advancement in the field of energy storage solutions, positioning the IWC-MSCs as a pivotal development in enhancing the efficiency and capacity of modern energy systems. Simultaneously, with the continuous optimization of integrated devices, Duan et al. [106] Demonstrated square coils through a comparison of fixed WCC (F-WCC) and gradually changed WCC (G-WCC). G-WCC exhibits a gradual transition from coarse to fine, with significantly higher magnetic field intensity in the central regions of both the primary and secondary coils compared to the edge areas, which results in a more uniform current distribution in G-WCC (Fig. 5e). Furthermore, the ohmic losses in G-WCC are superior to those in F-WCC, thereby reducing heat generation during the transmission process (Fig. 5f).

The fabrication techniques for integrated systems primarily include screen-printing technology [107], lithographic patterning [108], and direct ink writing [109]. Compared to screen printing, lithographic patterning offers greater precision in positioning the required components, which plays a crucial role in manufacturing seamless and compact devices. The structure from simple external physical connections to shared electrode connections, and finally to seamless internal shared electrode integration, has gradually improved spatial efficiency and the overall compactness of the devices, thereby enhancing energy transfer efficiency.

4.2. Applications

The integrated devices are primarily used for energy transmission as power modules on irregular object surfaces, and applied as flexible conformal power modules in wearable medical devices such as electronic skins and implantable bioelectronic devices.

4.2.1. Electronic equipment

Electronic equipment refers to devices or systems that operate using electronic circuits and components, which are evolving to be lighter and more portable. Accordingly, an excellent energy storage device like FSCs is indispensable. For FSCs, it is imperative to replenish their energy in a timely manner without the wired external power connections. For instance, Pandey et al. [98] have proposed integrating supercapacitors

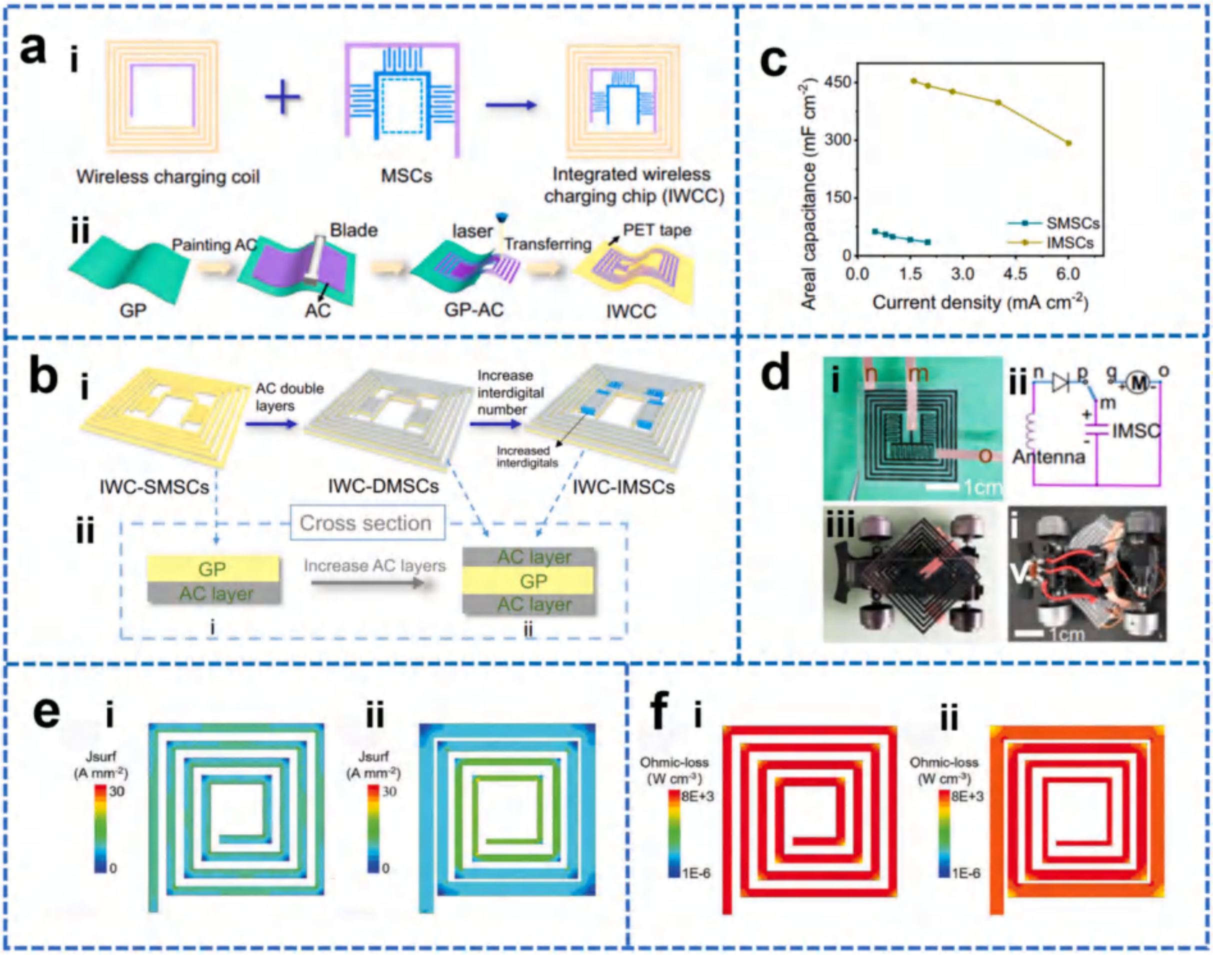

Fig. 5. The design, fabrication, performance and application of MSCs. a) (i) Combination of WCC and MSCs in the integrated device IWC-MSCs. (ii) The schematic illustration of the integrated device. b) (i) Schematic diagrams of MSCs in IWC-MSCs. (ii) Change of cross-section of SMSCs, DMSCs, and IMSCs. c) Rate capacity curves of MSCs of SMSCs and IMSCs, respectively. d) (i) An image of the connecting details of IWC-IMSCs using copper foils as conductors. "m", "n", "o" copper foils respectively correspond to "m", "n", "o" point in (ii). (ii) The circuit diagram of the IWC-IMSCs assembling with the car. (iii) The downside of the car assembled with IWC-IMSCs. (iv) The upside of the car connecting with a switch adopted from [105]. e) Surface current distribution of the MXene-based WCC at 100 kHz. f) Ohmic loss of the MXene-based WCC adopted from [106].

into wireless charging biomedical sensors. The supercapacitors in the sensor can operate via wireless charging, which can eliminate the reliance on traditional batteries. This approach enables rapid charging of supercapacitors to power the sensor, thereby extending its operational lifespan, and is considered an alternative energy storage solution to conventional batteries.

In addition to powering biomedical sensors, integrated devices can also conformally adhere to surfaces of irregularly shaped objects to supply power, which allows these objects to move freely without the hindrance of wires. For instance, Gao et al. [105] have successfully demonstrated the practical application of IWC-MSCs by replacing a conventional columnar battery in powering an electric toy car. Following a brief 6-min charge, these MSCs delivered an impressive power output of 45.9 mW, which showcases their potential for efficient energy storage and partially replacing conventional rigid batteries in real-world applications (Fig. 5d). The wireless power receiver charges the MSCs, and the LED bulb lights up during the charging process (Fig. 6a-(i)) [103]. This energy powers the photoconductive detector of perovskite NWs, enabling it to capture ultraviolet, visible, and infrared light and convert it into a stable electrical signal (Fig. 6a-(ii)). The system demonstrates a consistent photocurrent response, highlighting its reliability in various light conditions. The objects mounted with flexible integrated devices can better adapt to multiple scenarios and applications.

4.2.2. Biomedical equipment

Biomedical equipment is the instrument used to diagnose and monitor the patient condition, which plays a vital role in modern medicine. The most emphasized aspects of biomedical equipment are integration and safety [111]. The FSCs with wireless charging obviate the need for contact electrodes and can be seamlessly applied to non-uniform surfaces such as skin. Therefore, FSCs are widely used due to their high-power density and high cycle stability. To address this, Gao et al. [110] have employed an innovative technique, utilizing a solution mixture evaporation method to fabricate ultra-thin films. This method not only preserves the structural integrity but also seamlessly integrates the coil and MSCs, significantly enhancing the adaptability and efficiency of devices on uneven surfaces. This approach marks a significant advancement in the design of wearable electronic devices, optimizing both their aesthetic and functional attributes. The essence of this system ingenuity is encapsulated in the synthesis process, where the substrate, electrode, and electrolyte are intricately interwoven through evaporation from liquid precursors, culminating in a robust and cohesive structure (Fig. 6b). This meticulous design allows the wireless coil to attain impressive electrical outputs—achieving a maximum current of 0.3 mA and a voltage of 2.1 V, all at a mere 0.5 cm from the wireless transmitter. Notably, the device is exceptionally lightweight at 166 ± 4 mg and boasts an adjustable electrode thickness ranging from 11.7 to 112.5 μm, with a remarkable capacitance of 11.39 F cm^{-3} at the current

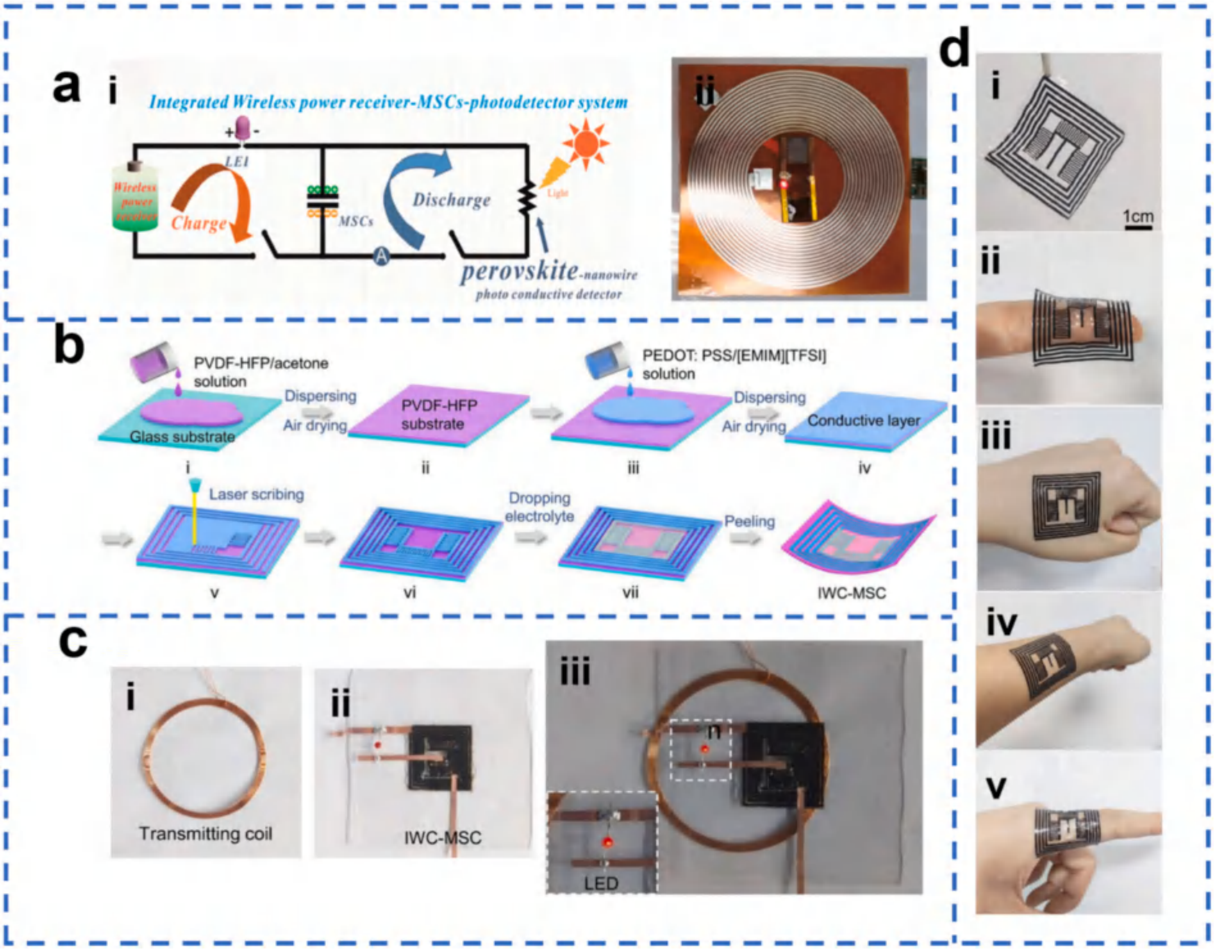

Fig. 6. (a) (i) Circuit diagram of integrated system. The system consists of the coil as power receiver, MSCs, and photoconductive-type photodetectors of perovskite NWs adopted from [103]. (ii) Photograph of the integrated system. b) Fabrication process of IWC-MSC. (c) (i)The wireless transmitting coil of wireless transmitter. (ii) The wireless charging receiver. (iii) A picture of wireless charging system during wireless charging. The inset is red LED lighting during wireless charging. (d) (i) (ii) Pictures of the flexible and thin IWC-MSC (iii) Image of IWC-MSC attaching conformably on the human fist (iv) arm and (v) finger adopted from [110].

density of 64.3 mA cm^{-3}. A standout feature of the IWC-MSC is its remarkable flexibility and conformity to human skin contours such as fists, arms, and fingers (Fig. 6d). This characteristic ensures minimal performance degradation even when subjected to significant deformation—a critical advantage for powering electronic skin and compatible wearable devices. The wireless coil can light a small lamp after collecting enough power. This feature underscores its potential in real-world applications, making it a pivotal development in the realm of wearable electronics.

For implanted biomedical devices, traditional battery-powered devices have weak power, poor stability, and are connected with external wires, which do not adequately meet the requirements for mobility in biomedical implant power modules. Additionally, external wires can easily induce infections. Therefore, Sheng et al. [112] have developed a soft, wireless implantable power system consisting of a wireless charging module and an energy storage module. Biocompatibility is paramount in implantable devices, thus sodium alginate (Alg—Na) is chosen as the electrolyte, known for its good biocompatibility/biodegradability, high conductivity, and stability. By directly ionically cross-linking Zn^{2+} with Alg—Na, a quasi-solid-state gel electrolyte membrane has been developed that fully degrades Alg-Zn electrolyte membranes to date (Fig. 7a). In addition to the electrolyte membrane, zinc and molybdenum are essential trace elements for human growth and development, making zinc an ideal anode and molybdenum disulfide a suitable cathode. Their daily intake far exceeds the dissolution dose of the implantable device. The energy can be transmitted wireless to receiving coil made of magnesium (Mg) by a receiving antenna with biodegradable Mo interconnects, then to rectifier coil. After rectifying, it can generate stabilized and sustained DC power to store energy by supercapacitors or directly charge electronic devices. Under this circumstance, a 30-turn Mg coil is sufficient to induce (Fig. 7b).

To tackle the issue of drug leakage during implantation and pulsed drug release, Sheng et al. [112] have created an innovative drug delivery device. This compact, biodegradable device is driven by an electric field and can be wirelessly powered. Once a direct current voltage is applied, electrodes generate an electric field to facilitate the movement of charged drug molecules for diffusion through the separation membrane. The integrated power system module and drug delivery module are interconnected, allowing simultaneous operation (Fig. 7c). When an external transmitting coil nears, the Mg receiving coil transfers energy to the rectifier and converts it into DC power. Through parallel connection, this DC current not only facilitates ionic drug release but also charges the capacitor. Following disconnection of the external voltage, the energy storage module effectively sustains drug release and thus ensuring prolonged operational efficiency.

5. Conclusion and prospects

This review introduces the flexible wireless charging energy storage devices, and analyzes its importance in the field of flexible electronics from its structure and existing application cases. It first summarizes the types of wireless charging, and specifically expounds the principle and

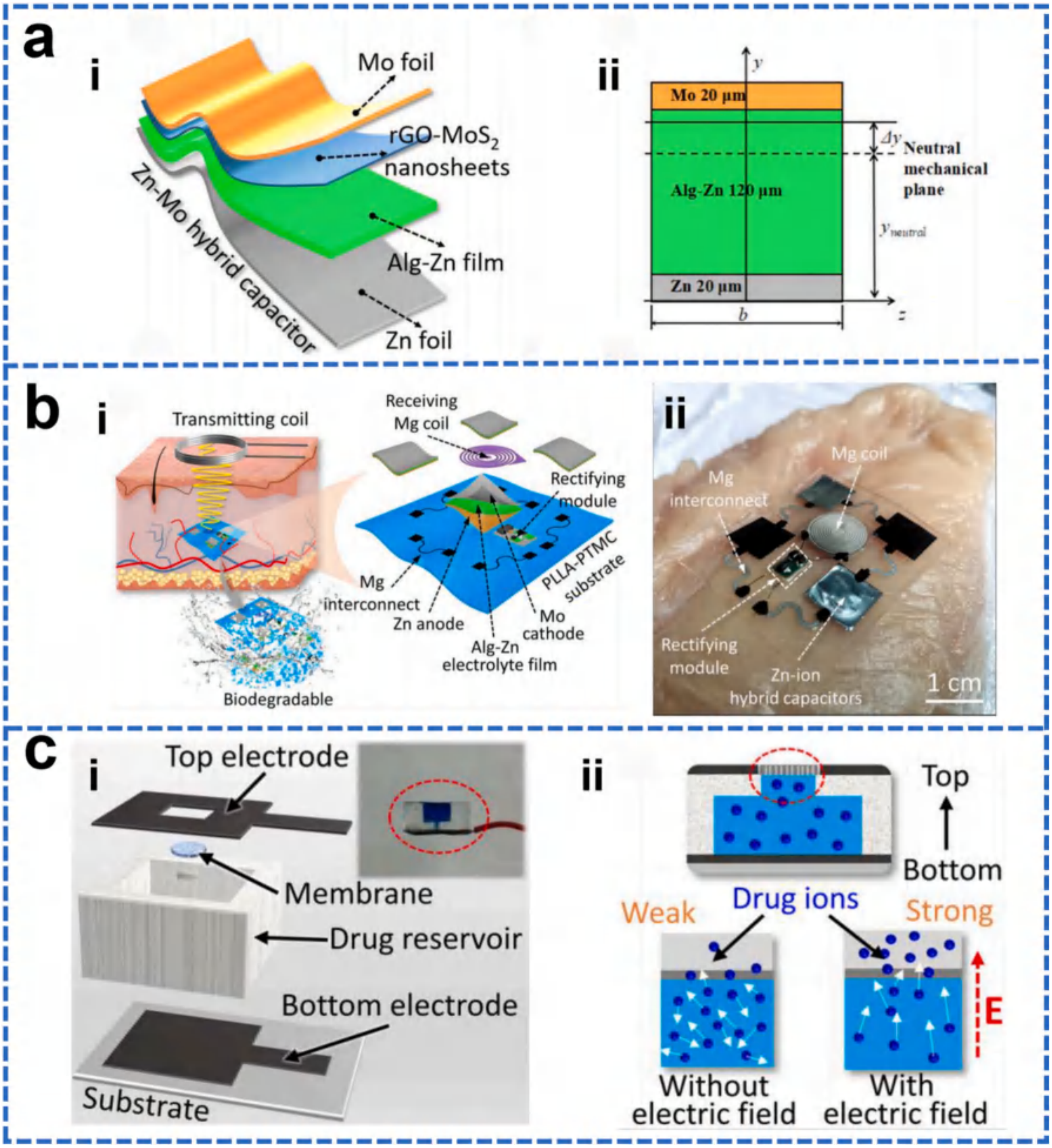

Fig. 7. a) (i) Schematic illustration for the flexible Zn-MoS_2 HSCs based on the Alg-Zn electrolyte film. (ii) Schematic diagram of the cross section of Zn-ion HSCs. b) (i) Illustration of the device structure. (ii) Photograph of the integrated energy supply system attached to the muscle tissue. c) (i) Schematic view of the biodegradable drug release device. Inset: Side view of the internal drug reservoir filled with the model drug. (ii) Schematic illustrations of the drug release mechanism from the device adopted from [112].

application scenarios of inductive coupling, magnetic resonance coupling and RF radiation. Then, the basic concept of FSCs is briefly introduced, which can be divided into EDLCs, PCs and HSCs according to the energy storage mechanism, and their principles are explained respectively. Integrating wireless charging with FSCs is considered as a feasible strategy to improve the existing limitations and deficiencies of FSCs. Finally, the researches of wireless charging energy storage devices in recent years are summarized, which fully proves the feasibility and high convenience of wireless charging and energy storage integration equipment. Although significant advancements have been achieved, there remains some obstacles and challenges that warrant further investigations.

At present, flexible wireless charging energy storage devices still face some problems such as low transmission efficiency, poor charging stability, and limited bending angle, which greatly limits their wider application range. In recent work, the transmission efficiency of inductive coupling has reached 52.8 %, yet it remains notably below the anticipated target. Optimizing coil design is key to improve transmission efficiency [105]. In addition to the planar coaxial structure mentioned above, the following developments will focus on optimizing the coil turn ratio and refining the size and shape to maximize coupling efficiency. Resonant coupling not only emphasizes the optimization of coil design, but also requires more accurate matching of resonant frequencies between the transmitting and receiving ends. In addition, effective RF transmission requires well-designed shielding measures to mitigate external electromagnetic interference and other wireless signals.

To date, integrated wireless charging systems have yet to achieve consistently reliable performance across each charging cycle. Specifically, the time required to charge a device from fully depleted to a full charge remains variable and unpredictable. This issue requires ongoing research and development into more advanced alignment technologies to ensure optimal positioning between the transmitter and receiver coils. One potential solution is the incorporation of real-time tracking and positioning systems. These could utilize sensors, motors, or even computer vision to continuously monitor the relative alignment of the transmitter and receiver, and automatically adjust their positions to maintain optimal coupling. This dynamic alignment would help compensate for factors like device movement or placement variations, ensuring a more consistent and efficient charging experience.

To better integrate wireless charging capabilities with energy storage systems, the choice of flexible materials has become a key factor. Under external forces like bending, stretching, and compression, flexible materials can help maintain the performance of the integrated device. Flexible substrates enable device structures to be printed or deposited through processes such as solution evaporation, printing, and laser etching. This approach allows the integrated devices to exhibit improved inter-device compatibility, adhesion, and conformal properties compared to rigid, inflexible systems. For example, thin-film batteries or supercapacitors fabricated on flexible polymer sheets could be seamlessly integrated with flexible wireless charging coils. The conformable nature of these materials would enable the entire energy storage and charging system to flex, stretch, and bend without compromising functionality. This flexibility is crucial for applications like wearable electronics, soft robotics, and conformable power sources for unique product designs. Beyond just material selection, the manufacturing techniques used to integrate the wireless charging and energy storage components are also important. Additive processes like 3D printing or direct ink writing allow the entire system to be co-fabricated as a single, monolithic structure. This avoids the need for discrete components and assembly, further enhancing the robustness and reliability of the integrated device under mechanical stress.

Flexible wireless charging and energy storage devices present significant application value and promising market prospects, particularly in the rapidly advancing fields of wearable electronics [113], smart textiles [114], and the IoT [115]. These devices offer a seamless and efficient energy transfer mechanism and their inherent flexibility allows for integration into a wide range of substrates. Moreover, the integration of energy storage capabilities into flexible wireless charging systems facilitates the development of self-sustaining devices, where energy harvesting and storage occur simultaneously, providing greater autonomy and reducing dependency on external power sources. As consumer demand for portable, wearable, and smart devices continues to grow, the market for such flexible, wireless energy solutions is expected to expand significantly. Advancements in materials science, including the development of FSCs and high-efficiency wireless charging technologies, are expected to further propel the commercial viability and functionality of these devices, positioning them as a key enabler of next-generation electronic systems.

As wearable devices [116], flexible displays [117], and IoT-enabled systems [118] become more prevalent, the need for power solutions that can seamlessly integrate into dynamic, flexible environments becomes critical. Furthermore, the convergence of energy storage and wireless charging in a single flexible device is essential for creating self-sustaining technologies, where efficient energy harvesting and storage can occur simultaneously. The necessity for such systems is amplified by the growing trend towards autonomous, environmentally sustainable devices that reduce the dependency on conventional power sources. Wireless charging technology has already expanded into diverse applications, ranging from small-scale devices like smartphone chargers and Wi-Fi routers, to larger-scale systems such as satellite communications and receiving antennas that are ubiquitous in our surroundings. At the same time, AI-driven energy storage and all-transparent electrodes represent promising research directions with transformative potential [119]. AI has the ability to optimize energy storage systems by improving battery management and identifying novel materials for more efficient storage solutions [120]. Concurrently, AI accelerates the development of all-transparent electrodes by discovering advanced materials that enhance conductivity, flexibility, and transparency, paving the way for next-generation electronics [121]. Looking to the future, wireless energy transmission holds promise as a more environmentally friendly and sustainable power source. This technology could potentially revolutionize how we power devices and facilities, enabling scenarios like high-power wireless charging for electric vehicles stationed in designated charging zones. Moreover, ongoing advancements in FSCs offer opportunities to improve both the energy and power densities of wireless power systems. Wireless power transmission can seamlessly penetrate the skin, allowing wireless charging and energy storage integrated devices to effectively eliminate the risk of wired infection. Integrating wireless charging systems with FSCs holds particular promise for significant advancements in wearable devices and medical applications.

CRediT authorship contribution statement

Yihang Cao: Writing – review & editing, Writing – original draft. **Yunshuo Zhang:** Conceptualization, Writing – review & editing. **Yuzhe Chen:** Writing – review & editing. **Xuan Zhang:** Data curation, Visualization. **Ning Ding:** Software, Conceptualization. **Xiang Zou:** Supervision. **Mingze Wang:** Supervision. **Shujuan Liu:** Writing – review & editing. **Weiwei Zhao:** Writing – review & editing. **Qiang Zhao:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by National Natural Science Foundation of China (62174086), (62474096) and (62288102), Outstanding Youth Foundation of Jiangsu Province (BK20240139), Basic Research Program of Jiangsu (BK20243057), Innovation Support Programme (Soft Science Research) Project Achievements of Jiangsu Province (BK20231514), Qinglan Project of Jiangsu Province of China, Postgraduate Research & Practice Innovation Program of Jiangsu Province (KYCX23_0985), and Jiangsu Province Science and Technology Innovation Training Program (202410293156Y).

Data availability

No data was used for the research described in the article.

References

[1] Z. Hui, L. Zhang, G. Ren, G. Sun, H.D. Yu, W. Huang, Green flexible electronics: Natural materials, fabrication, and applications, Adv. Mater. 35 (2023) 2211202, https://doi.org/10.1002/adma.202211202.
[2] W. Heng, S. Solomon, W. Gao, Flexible electronics and devices as human–machine interfaces for medical robotics, Adv. Mater. 34 (2022) 2107902, https://doi.org/10.1002/adma.202107902.
[3] T. Xing, A. He, Z. Huang, Y. Luo, Y. Zhang, M. Wang, Z. Shi, G. Ke, J. Bai, S. Zhao, Silk-based flexible electronics and smart wearable textiles: Progress and beyond, Chem. Eng. J. (2023) 145534, https://doi.org/10.1016/j.cej.2023.145534.
[4] Z. Zhao, K. Liu, Y. Liu, Y. Guo, Y. Liu, Intrinsically flexible displays: Key materials and devices, Natl. Sci. Rev. 9 (2022) nwac090, https://doi.org/10.1093/nsr/nwac090.
[5] S. Zhang, B. Yin, C. Liu, Z. Wang, D. Gu, A lightweight, compressible and portable sponge-based supercapacitor for future power supply, Chem. Eng. J. 349 (2018) 509–521, https://doi.org/10.1016/j.cej.2018.05.125.
[6] S. Hui, Planar wireless charging technology for portable electronic products and Qi, Proc. IEEE. 101 (2013) 1290–1301, https://doi.org/10.1109/JPROC.2013.2246531.
[7] S. Hild, S. Leavey, C. Gräf, B. Sorazu, Smart charging technologies for portable electronic devices, IEEE Trans. Smart Grid 5 (2013) 328–336, https://doi.org/10.1109/TSG.2013.2281853.

[8] W. Zhao, M. Jiang, W. Wang, S. Liu, W. Huang, Q. Zhao, Flexible transparent supercapacitors: materials and devices, Adv. Funct. Mater. 31 (2021) 2009136, https://doi.org/10.1002/adfm.202009136.
[9] X. Lu, P. Wang, D. Niyato, D.I. Kim, Z. Han, Wireless charging technologies: Fundamentals, standards, and network applications, IEEE Commun. Surv. Tutor. 18 (2015) 1413–1452, https://doi.org/10.1109/COMST.2015.2499783.
[10] Y. Yun, K.R. Nandanapalli, J.H. Choi, W. Son, C. Choi, S. Lee, Extremely flexible and mechanically durable planar supercapacitors: High energy density and low-cost power source for E-skin electronics, Nano Energy 78 (2020) 105356, https://doi.org/10.1016/j.nanoen.2020.105356.
[11] Q. Xue, J. Sun, Y. Huang, M. Zhu, Z. Pei, H. Li, Y. Wang, N. Li, H. Zhang, C. Zhi, Recent progress on flexible and wearable supercapacitors, Small 13 (2017) 1701827, https://doi.org/10.1002/smll.201701827.
[12] Y.I. Kim, E. Samuel, B. Joshi, M.W. Kim, T.G. Kim, M.T. Swihart, S.S. Yoon, Highly efficient electrodes for supercapacitors using silver-plated carbon nanofibers with enhanced mechanical flexibility and long-term stability, Chem. Eng. J. 353 (2018) 189–196, https://doi.org/10.1016/j.cej.2018.07.066.
[13] L. Sun, D. Ma, H. Tang, A review of recent trends in wireless power transfer technology and its applications in electric vehicle wireless charging, Renew. Sustain. Energy Rev. 91 (2018) 490–503, https://doi.org/10.1016/j.rser.2018.04.016.
[14] A.A. Eteng, S.K.A. Rahim, C.Y. Leow, S. Jayaprakasam, B.W. Chew, Low-power near-field magnetic wireless energy transfer links: A review of architectures and design approaches, Renew. Sustain. Energy Rev. 77 (2017) 486–505, https://doi.org/10.1016/j.rser.2017.04.051.
[15] Z. Popović, E.A. Falkenstein, D. Costinett, R. Zane, Low-power far-field wireless powering for wireless sensors, Proc. IEEE 101 (2013) 1397–1409, https://doi.org/10.1109/JPROC.2013.2244053.
[16] A.D. Chave, J.R. Booker, Electromagnetic induction studies, Rev. Geophys. 25 (1987) 989–1003, https://doi.org/10.1029/RG025i005p00989.
[17] S.D. Barman, A.W. Reza, N. Kumar, M.E. Karim, A.B. Munir, Wireless powering by magnetic resonant coupling: Recent trends in wireless power transfer system and its applications, Renew. Sustain. Energy Rev. 51 (2015) 1525–1552, https://doi.org/10.1016/j.rser.2015.07.031.
[18] F. Marra, L. Zhang, J.G. Lyng, Radio frequency treatment of foods: Review of recent advances, J. Food Eng. 91 (2009) 497–508, https://doi.org/10.1016/j.jfoodeng.2008.10.015.
[19] W.C. Brown, The history of wireless power transmission, Sol. Energy 56 (1996) 3–21, https://doi.org/10.1016/0038-092X(95)00080-B.
[20] C.C. Popescu, K. Aryana, P. Garud, K.P. Dao, S. Vitale, V. Liberman, H.B. Bae, T. W. Lee, M. Kang, K.A. Richardson, Electrically reconfigurable phase-change transmissive metasurface, Adv. Mater. (2024) 2400627, https://doi.org/10.1002/adma.202400627.
[21] Y.e. Jiang, L. Wang, H. Chen, X. Shen, Physical layer covert communication in B5G wireless networks—Its research, applications, and challenges, Proc. IEEE. 112 (2024), https://doi.org/10.1109/JPROC.2024.3364256.
[22] A. Costanzo, M. Dionigi, D. Masotti, M. Mongiardo, G. Monti, L. Tarricone, R. Sorrentino, Electromagnetic energy harvesting and wireless power transmission: A unified approach, Proc. IEEE 102 (2014) 1692–1711, https://doi.org/10.1109/jproc.2014.2355261.
[23] T. Biswas, P. Ghosh, B. Manna, A. Banerji, S.K. Biswas, Non-radiative wireless power transfer using inductive resonance coupling, in: 2017 IEEE Calcutta Conference (CALCON), IEEE, 2017, pp. 479–483, https://doi.org/10.1109/CALCON.2017.8280780.
[24] H.H. Wu, A. Gilchrist, K.D. Sealy, D. Bronson, A high efficiency 5 kW inductive charger for EVs using dual side control, IEEE Trans. Industr. Inform. 8 (2012) 585–595, https://doi.org/10.1109/tii.2012.2192283.
[25] N. Shinohara, The wireless power transmission: Inductive coupling, radio wave, and resonance coupling, WIREs Energy Environ. 1 (2012) 337–346, https://doi.org/10.1002/wene.43.
[26] M. Fareq, M. Fitra, M. Irwanto, S. Hasan, M. Arinal, Low wireless power transfer using inductive coupling for mobile phone charger, J. Phys. Conf. Ser. (2014) 012019, https://doi.org/10.1088/1742-6596/495/1/012019. IOP Publishing.
[27] J.K. Nama, A.K. Verma, M. Srivastava, P.S. Tomar, An efficient inductive power transfer topology for electric vehicle battery charging, IEEE Trans. Ind. Appl. 56 (2020) 6925–6936, https://doi.org/10.1109/tia.2020.3018419.
[28] E.G. Marques, V.S. Costa, A.M.S. Mendes, M.S. Perdigão, Inductive power transfer in electric vehicles: Past and future trends, IEEE Veh. Technol. Mag. 18 (2023) 111–122, https://doi.org/10.1109/mvt.2023.3318840.
[29] V.K. Bandari, Y. Nan, D. Karnaushenko, Y. Hong, B. Sun, F. Striggow, D. D. Karnaushenko, C. Becker, M. Faghih, M. Medina-Sánchez, F. Zhu, O. G. Schmidt, A flexible microsystem capable of controlled motion and actuation by wireless power transfer, Nat. Electron. 3 (2020) 172–180, https://doi.org/10.1038/s41928-020-0384-1.
[30] A. Karalis, J.D. Joannopoulos, M. Soljačić, Efficient wireless non-radiative mid-range energy transfer, Ann. Phys. 323 (2008) 34–48, https://doi.org/10.1016/j.aop.2007.04.017.
[31] S. Gervasoni, N. Pedrini, T. Rifai, C. Fischer, F.C. Landers, M. Mattmann, R. Dreyfus, S. Viviani, A. Veciana, E. Masina, A human-scale clinically ready electromagnetic navigation system for magnetically responsive biomaterials and medical devices, Adv. Mater. (2024) 2310701, https://doi.org/10.1002/adma.202310701.
[32] G. Liu, B. Zhang, W. Xiao, D. Qiu, Y. Chen, J. Guan, Omnidirectional wireless power transfer system based on rotary transmitting coil for household appliances, Energies 11 (2018) 878, https://doi.org/10.3390/en11040878.
[33] D. Ahn, S. Hong, Wireless power transmission with self-regulated output voltage for biomedical implant, IEEE Trans Ind Electron 61 (2014) 2225–2235, https://doi.org/10.1109/tie.2013.2273472.
[34] S. Niu, H. Xu, Z. Sun, Z.Y. Shao, L. Jian, The state-of-the-arts of wireless electric vehicle charging via magnetic resonance: principles, standards and core technologies, Renew. Sustain. Energy Rev. 114 (2019) 109302, https://doi.org/10.1016/j.rser.2019.109302.
[35] A. Kurs, A. Karalis, R. Moffatt, J.D. Joannopoulos, P. Fisher, M. Soljacic, Wireless power transfer via strongly coupled magnetic resonances, Science 317 (2007) 83–86, https://doi.org/10.1126/science.1143254.
[36] B. Clerckx, R. Zhang, R. Schober, D.W.K. Ng, D.I. Kim, H.V. Poor, Fundamentals of wireless information and power transfer: From RF energy harvester models to signal and system designs, IEEE J Sel Areas Commun 37 (2019) 4–33, https://doi.org/10.1109/jsac.2018.2872615.
[37] B. Shao, C. Lu, Y. Xiang, F. Li, M. Song, Comprehensive review of RF MEMS switches in satellite communications, Sensors 24 (2024) 3135, https://doi.org/10.3390/s24103135.
[38] U.C. Nnamdi, I.B. Asianuba, Wireless power transfer: A review of existing technologies, Eur. J. Eng. Technol. Res. 8 (2023) 59–66, https://doi.org/10.24018/ejeng.2023.8.3.3038.
[39] C. Pan, H. Ren, K. Wang, M. Elkashlan, A. Nallanathan, J. Wang, L. Hanzo, Intelligent reflecting surface aided MIMO broadcasting for simultaneous wireless information and power transfer, IEEE J Sel Areas Commun 38 (2020) 1719–1734, https://doi.org/10.1109/jsac.2020.3000802.
[40] S. Khairy, M. Han, L.X. Cai, Y. Cheng, Sustainable wireless IoT networks with RF energy charging over Wi-Fi (CoWiFi), IEEE Internet Things J. 6 (2019) 10205–10218, https://doi.org/10.1109/jiot.2019.2936837.
[41] Z. Kudaibergenova, K. Dautov, M. Hashmi, Compact metamaterial-integrated wireless information and power transfer system for low-power IoT sensors, Alex. Eng. J. 92 (2024) 176–184, https://doi.org/10.1016/j.aej.2024.02.058.
[42] S.A. Mirbozorgi, H. Bahrami, M. Sawan, B. Gosselin, A smart multicoil inductively coupled array for wireless power transmission, IEEE Trans Ind Electron 61 (2014) 6061–6070, https://doi.org/10.1109/TIE.2014.2308138.
[43] J. Dai, D.C. Ludois, A survey of wireless power transfer and a critical comparison of inductive and capacitive coupling for small gap applications, IEEE Trans. Power Electron. 30 (2015) 6017–6029, https://doi.org/10.1109/TPEL.2015.2415253.
[44] M. Friedman, F. Fernsler, Low-loss RF transport over long distances, IEEE Trans. Microw. Theory Tech. 49 (2001) 341–348, https://doi.org/10.1109/22.903095.
[45] L. Cui, Z. Zhang, N. Gao, Z. Meng, Z. Li, Radio frequency identification and sensing techniques and their applications—a review of the state-of-the-art, Sensors 19 (2019) 4012, https://doi.org/10.3390/s19184012.
[46] H. Nesser, H.A. Mahmoud, G. Lubineau, High-sensitivity RFID sensor for structural health monitoring, Adv. Sci. 10 (2023) 2301807, https://doi.org/10.1002/advs.202301807.
[47] H. Du, NFC technology: Today and tomorrow, Int. J. Future Comput. Commun. 2 (2013) 351, https://doi.org/10.7763/ijfcc.2013.v2.183.
[48] M. Pulipati, S. Phani, Comparison of various short range wireless communication technologies with NFC, Inter. J. Sci. Res. 2 (2013) 87–91. https://www.researchgate.net/publication/306504089.
[49] J. Wang, J. Zhang, K. Li, C. Pan, C. Majidi, S. Kumar, Locating Everyday Objects Using NFC Textiles, Proceedings of the 20th International Conference on Information Processing in Sensor Networks (co-located with CPS-IoT Week 2021), 2021, pp. 15–30, https://doi.org/10.1145/3412382.3458254.
[50] J. Tosi, F. Taffoni, M. Santacatterina, R. Sannino, D. Formica, Performance evaluation of Bluetooth low energy: A systematic review, Sensors 17 (2017) 2898, https://doi.org/10.3390/s17122898.
[51] M.K. Wallin, S. Wajntraub, Evaluation of Bluetooth as a replacement for cables in intensive care and surgery, Anesth. Analg. 98 (2004) 763–767, https://doi.org/10.1213/01.ANE.0000097186.99167.BA.
[52] K. Pahlavan, P. Krishnamurthy, Evolution and impact of Wi-Fi technology and applications: A historical perspective, Int. J. Wireless Inf. Networks 28 (2021) 3–19, https://doi.org/10.1007/s10776-020-00501-8.
[53] J. Mesquita, D. Guimarães, C. Pereira, F. Santos, L. Almeida, Assessing the ESP8266 WiFi module for the internet of things, in: 2018 IEEE 23rd International Conference on Emerging Technologies and Factory Automation (ETFA), IEEE, 2018, pp. 784–791, https://doi.org/10.1109/ETFA.2018.8502562.
[54] Y.J. Tu, S. Piramuthu, On addressing RFID/NFC-based relay attacks: An overview, Decis. Support. Syst. 129 (2020) 113194, https://doi.org/10.1016/j.dss.2019.113194.
[55] L.J. Chen, R. Kapoor, K. Lee, M. Sanadidi, M. Gerla, Audio Streaming over Bluetooth: An Adaptive ARQ Timeout Approach, 24th International Conference on Distributed Computing Systems Workshops, 2004. Proceedings, IEEE, 2004, pp. 196–201, https://doi.org/10.1109/ICDCSW.2004.1284031.
[56] N. Vikram, K. Harish, M. Nihaal, R. Umesh, S.A.A. Kumar, A Low Cost Home Automation System Using Wi-Fi Based Wireless Sensor Network Incorporating Internet of Things (IoT), in: 2017 IEEE 7th International Advance Computing Conference (IACC), IEEE, 2017, pp. 174–178, https://doi.org/10.1109/IACC.2017.0048.
[57] H. Shan, J. Peterson Iii, S. Hathorn, S. Mohammadi, The RFID connection: RFID Technology for Sensing and the Internet of Things, IEEE Microw. Mag. 19 (2018) 63–79, https://doi.org/10.1109/mmm.2018.2863439.
[58] F. Costa, S. Genovesi, M. Borgese, A. Michel, F.A. Dicandia, G. Manara, A review of RFID sensors, the new frontier of internet of things, Sensors 21 (2021) 3138, https://doi.org/10.3390/s21093138.

[59] S. Hussain, N. Bhadri, M.S. Hussain, Advancements in wireless communication, Int. J. Electron. Commun. Eng. 7 (2020) 1–4, https://doi.org/10.14445/23488549/ijece-v7i9p101.

[60] D. Eridani, A.F. Rochim, F.N. Cesara, Comparative Performance Study of ESP-NOW, Wi-Fi, Bluetooth Protocols Based on Range, Transmission Speed, Latency, Energy Usage and Barrier Resistance, in: 2021 International seminar on application for technology of information and communication (iSemantic), IEEE, 2021, pp. 322–328, https://doi.org/10.1109/iSemantic52711.2021.9573246.

[61] R. Challoo, A. Oladeinde, N. Yilmazer, S. Ozcelik, L. Challoo, An overview and assessment of Wireless technologies and co- existence of ZigBee, Bluetooth and Wi-Fi devices, Procedia Comput. Sci. 12 (2012) 386–391, https://doi.org/10.1016/j.procs.2012.09.091.

[62] T. Guo, D. Zhou, W. Liu, J. Su, Recent advances in all-in-one flexible supercapacitors, Sci. China Mater. 64 (2020) 27–45, https://doi.org/10.1007/s40843-020-1417-8.

[63] Y. Shao, M.F. El-Kady, J. Sun, Y. Li, Q. Zhang, M. Zhu, H. Wang, B. Dunn, R. B. Kaner, Design and mechanisms of asymmetric supercapacitors, Chem. Rev. 118 (2018) 9233–9280, https://doi.org/10.1021/acs.chemrev.8b00252.

[64] A. He, J. He, L. Cao, J. Chen, B. Cheng, R. Ma, Y. Ding, G. Yang, F. Yi, Flexible supercapacitor integrated systems, Adv. Mater. Technol. 9 (2024) 2301931, https://doi.org/10.1002/admt.202301931.

[65] C. Lu, X. Chen, Latest advances in flexible symmetric supercapacitors: From material engineering to wearable applications, Acc. Chem. Res. 53 (2020) 1468–1477, https://doi.org/10.1021/acs.accounts.0c00205.

[66] L. Li, Z. Lou, D. Chen, K. Jiang, W. Han, G. Shen, Recent advances in flexible/stretchable supercapacitors for wearable electronics, Small 14 (2018) 1702829, https://doi.org/10.1002/smll.201702829.

[67] M.R. Islam, S. Afroj, K.S. Novoselov, N. Karim, Smart electronic textile-based wearable supercapacitors, Adv. Sci. 9 (2022) 2203856, https://doi.org/10.1002/advs.202203856.

[68] H. Sheng, Y. Ma, H. Zhang, J. Yuan, F. Li, W. Li, E. Xie, W. Lan, Integration of supercapacitors with sensors and energy-harvesting devices: A review, Adv. Mater. Technol. 9 (2024) 2301796, https://doi.org/10.1002/admt.202301796.

[69] A. Borenstein, O. Hanna, R. Attias, S. Luski, T. Brousse, D. Aurbach, Carbon-based composite materials for supercapacitor electrodes: A review, J Mater Chem A 5 (2017) 12653–12672, https://doi.org/10.1039/c7ta00863e.

[70] T. Jiang, Y. Wang, G.Z. Chen, Electrochemistry of titanium carbide MXenes in supercapacitor, Small Methods 7 (2023) 2201724, https://doi.org/10.1002/smtd.202201724.

[71] Y. Zhang, H. Mei, Y. Cao, X. Yan, J. Yan, H. Gao, H. Luo, S. Wang, X. Jia, L. Kachalova, J. Yang, S. Xue, C. Zhou, L. Wang, Y. Gui, Recent advances and challenges of electrode materials for flexible supercapacitors, Coord. Chem. Rev. 438 (2021) 213910, https://doi.org/10.1016/j.ccr.2021.213910.

[72] Y. Yan, T. Wang, X. Li, H. Pang, H. Xue, Noble metal-based materials in high-performance supercapacitors, Inorg. Chem. Front. 4 (2017) 33–51, https://doi.org/10.1039/c6qi00199h.

[73] L. Kouchachvili, E. Entchev, Ag/Biochar Composite for Supercapacitor Electrodes, Mater. Today, Energy 6 (2017) 136–145, https://doi.org/10.1016/j.mtener.2017.09.002.

[74] Y. Chen, X. Fu, Y. Yue, N. Zhang, J. Feng, H. Sun, Flexible and transparent supercapacitor based on ultrathin Au/graphene composite electrodes, Appl. Surf. Sci. 467 (2019) 104–111, https://doi.org/10.1016/j.apsusc.2018.10.093.

[75] L. Li, M. Zhang, X. Zhang, Z. Zhang, New Ti3C2 aerogel as promising negative electrode materials for asymmetric supercapacitors, J. Power Sources 364 (2017) 234–241, https://doi.org/10.1016/j.jpowsour.2017.08.029.

[76] A. González, E. Goikolea, J.A. Barrena, R. Mysyk, Review on supercapacitors: Technologies and materials, Renew. Sustain. Energy Rev. 58 (2016) 1189–1206, https://doi.org/10.1016/j.rser.2015.12.249.

[77] S. Huang, Z. Li, P. Li, X. Du, M. Ma, Z. Liang, Y. Su, L. Xiong, Ultrahigh-voltage aqueous electrolyte for wide-temperature supercapacitors, J Mater Chem A 11 (2023) 15532–15539, https://doi.org/10.1039/d3ta01639k.

[78] S. Sen, S.E. Goodwin, P.V. Barbará, G.A. Rance, D. Wales, J.M. Cameron, V. Sans, M. Mamlouk, K. Scott, D.A. Walsh, Gel–polymer electrolytes based on poly (ionic liquid)/ionic liquid networks, ACS Appl. Polym. Mater. 3 (2020) 200–208, https://doi.org/10.1021/acsapm.0c01042.

[79] J. Wu, Z. Rao, H. Wang, Y. Huang, Order-structured solid-state electrolytes, SusMat 2 (2022) 660–678, https://doi.org/10.1002/sus2.93.

[80] C. Zhong, Y. Deng, W. Hu, J. Qiao, L. Zhang, J. Zhang, A review of electrolyte materials and compositions for electrochemical supercapacitors, Chem. Soc. Rev. 44 (2015) 7484–7539, https://doi.org/10.1039/c5cs00303b.

[81] A. Abdisattar, M. Yeleuov, C. Daulbayev, K. Askaruly, A. Tolynbekov, A. Taurbekov, N. Prikhodko, Recent advances and challenges of current collectors for supercapacitors, Electrochem. Commun. 142 (2022) 107373, https://doi.org/10.1016/j.elecom.2022.107373.

[82] W. Zhao, T. Chen, W. Wang, S. Bi, M. Jiang, K.Y. Zhang, S. Liu, W. Huang, Q. Zhao, Layer-by-layer 2D ultrathin conductive $Cu_3(HHTP)_2$ film for high-performance flexible transparent supercapacitors, Adv. Mater. Interfaces 8 (2021) 2100308, https://doi.org/10.1002/admi.202100308.

[83] C. Zhan, C. Lian, Y. Zhang, M.W. Thompson, Y. Xie, J. Wu, P.R.C. Kent, P. T. Cummings, D.e. Jiang, D.J. Wesolowski, Computational insights into materials and interfaces for capacitive energy storage, Adv. Sci. 4 (2017) 1700059, https://doi.org/10.1002/advs.201700059.

[84] C. Wang, V. Strauss, R.B. Kaner, Carbon nanodots for capacitor electrodes, Trends Chem. 1 (2019) 858–868, https://doi.org/10.1016/j.trechm.2019.05.009.

[85] J. Zhao, Y. Jiang, H. Fan, M. Liu, O. Zhuo, X. Wang, Q. Wu, L. Yang, Y. Ma, Z. Hu, Porous 3D few-layer graphene-like carbon for ultrahigh-power supercapacitors with well-defined structure-performance relationship, Adv. Mater. 29 (2017) 1604569, https://doi.org/10.1002/adma.201604569.

[86] S. Fleischmann, J.B. Mitchell, R. Wang, C. Zhan, D.e. Jiang, V. Presser, V. Augustyn, Pseudocapacitance: From fundamental understanding to high power energy storage materials, Chem. Rev. 120 (2020) 6738–6782, https://doi.org/10.1021/acs.chemrev.0c00170.

[87] Q. Wu, Y. Zhang, G. Liu, X. Cui, S. Tao, H. Jiang, Y. Lin, R. Peng, X. Zhang, Z. Huang, Insights into pseudocapacitive mechanism of aqueous ammonium-ion supercapacitors with exceptional energy density and cyclability, Energy Storage Mater 70 (2024) 103474, https://doi.org/10.1016/j.ensm.2024.103474.

[88] A. Muzaffar, M.B. Ahamed, K. Deshmukh, J. Thirumalai, A review on recent advances in hybrid supercapacitors: design, fabrication and applications, Renew. Sustain. Energy Rev. 101 (2019) 123–145, https://doi.org/10.1016/j.rser.2018.10.026.

[89] A. Burke, R&D considerations for the performance and application of electrochemical capacitors, Electrochim. Acta 53 (2007) 1083–1091, https://doi.org/10.1016/j.electacta.2007.01.011.

[90] L.E. Helseth, The nonlinearities in the galvanostatic charging curves of supercapacitors provide insights into charging mechanisms, J Energy Storage 55 (2022) 105440, https://doi.org/10.1016/j.est.2022.105440.

[91] H. Li, L. Bai, H. Peng, J. Peng, Z. Huang, D. Gao, Optimal charging of supercapacitors with user-specified charging time, J Energy Storage 68 (2023) 107609, https://doi.org/10.1016/j.est.2023.107609.

[92] Q. Xie, C. Yi, H. Zhang, H. Xia, G. Xu, C. Miao, L. Yang, T. Shui, W. Zhang, Z. Sun, Stretchable Zn-ion hybrid capacitor with hydrogel encapsulated 3D interdigital structure, Adv. Energy Mater. 14 (2023) 2303592, https://doi.org/10.1002/aenm.202303592.

[93] C. Leng, Z. Zhao, Y. Song, L. Sun, Z. Fan, Y. Yang, X. Liu, X. Wang, J. Qiu, 3D carbon frameworks for ultrafast charge/discharge rate supercapacitors with high energy-power density, Nano Micro Lett. 13 (2021) 1–11, https://doi.org/10.1007/s40820-020-00535-w.

[94] J.R. Miller, R. Outlaw, B. Holloway, Graphene electric double layer capacitor with ultra-high-power performance, Electrochim. Acta 56 (2011) 10443–10449, https://doi.org/10.1016/j.electacta.2011.05.122.

[95] X. Chen, N.S. Villa, Y. Zhuang, L. Chen, T. Wang, Z. Li, T. Kong, Stretchable supercapacitors as emergent energy storage units for health monitoring bioelectronics, Adv. Energy Mater. 10 (2020) 1902769, https://doi.org/10.1002/aenm.201902769.

[96] Q. Zhang, S. Song, S. Dong, C. Zhu, Receiver-side-oriented simulator for dynamic wireless charging system with I-type transmitter and multiphase receiver, IEEE Trans. Ind. Electron. 68 (2020) 3906–3916, https://doi.org/10.1109/TIE.2020.2982087.

[97] J. Yun, C. Song, H. Lee, H. Park, Y.R. Jeong, J.W. Kim, S.W. Jin, S.Y. Oh, L. Sun, G. Zi, J.S. Ha, Stretchable array of high-performance micro-supercapacitors charged with solar cells for wireless powering of an integrated strain sensor, Nano Energy 49 (2018) 644–654, https://doi.org/10.1016/j.nanoen.2018.05.017.

[98] A. Pandey, F. Allos, A.P. Hu, D. Budgett, Integration of Supercapacitors into Wirelessly Charged Biomedical Sensors, 2011 6th IEEE Conference on Industrial Electronics and Applications, 2011, pp. 56–61, https://doi.org/10.1109/iciea.2011.5975550.

[99] K. Dimitriadou, N. Rigogiannis, S. Fountoukidis, F. Kotarela, A. Kyritsis, N. Papanikolaou, Current trends in electric vehicle charging infrastructure; Opportunities and challenges in wireless charging integration, Energies 16 (2023) 2057, https://doi.org/10.3390/en16042057.

[100] P. Vishnuram, S. Panchanathan, N. Rajamanickam, V. Krishnasamy, M. Bajaj, M. Piecha, V. Blazek, L. Prokop, Review of wireless charging system: Magnetic materials, coil configurations, challenges, and future perspectives, Energies 16 (2023) 4020, https://doi.org/10.3390/en16104020.

[101] B. Liu, H. Zhang, Z. Yang, P. Zhang, W. Ji, J. Liu, K. Li, J. He, P. Pan, Facile fabrication of oxygen and nitrogen co-doped 3D-carbon nanoarrays for high performance environmentally friendly wireless charging integration supercapacitor, J Energy Storage 49 (2022) 104082, https://doi.org/10.1016/j.est.2022.104082.

[102] S. Wang, S. Zheng, X. Shi, P. Das, L. Li, Y. Zhu, Y. Lu, X. Feng, Z.S. Wu, Monolithically integrated micro-supercapacitors with high areal number density produced by surface adhesive-directed electrolyte assembly, Nat. Commun. 15 (2024) 2850, https://doi.org/10.1038/s41467-024-47216-5.

[103] Y. Yue, Z. Yang, N. Liu, W. Liu, H. Zhang, Y. Ma, C. Yang, J. Su, L. Li, F. Long, Z. Zou, Y. Gao, A flexible integrated system containing a microsupercapacitor, a photodetector, and a wireless charging coil, ACS Nano 10 (2016) 11249–11257, https://doi.org/10.1021/acsnano.6b06326.

[104] S. Pan, J. Ren, X. Fang, H. Peng, Integration: An effective strategy to develop multifunctional energy storage devices, Adv. Energy Mater. 6 (2016) 1501867, https://doi.org/10.1002/aenm.201501867.

[105] C. Gao, J. Huang, Y. Xiao, G. Zhang, C. Dai, Z. Li, Y. Zhao, L. Jiang, L. Qu, A seamlessly integrated device of micro-supercapacitor and wireless charging with ultrahigh energy density and capacitance, Nat. Commun. 12 (2021) 2647, https://doi.org/10.1038/s41467-021-22912-8.

[106] Z. Duan, C. Hu, W. Liu, J. Liu, Z. Chu, W. Yang, L. Li, G. Shen, An all-MXene-Based flexible, seamless system with integrated wireless charging coil, micro-supercapacitor, and photodetector, Adv. Mater. Technol. 8 (2023) 2300157, https://doi.org/10.1002/admt.202300157.

[107] C. Chen, C. Ran, Q. Yao, J. Wang, C. Guo, L. Gu, H. Han, X. Wang, L. Chao, Y. Xia, Screen-printing technology for scale manufacturing of perovskite solar cells, Adv. Sci. 10 (2023) 2303992, https://doi.org/10.1002/advs.202303992.

[108] R.F. Pease, S.Y. Chou, Lithography and other patterning techniques for future electronics, Proc. IEEE 96 (2008) 248–270, https://doi.org/10.1109/JPROC.2007.911853.
[109] M. Saadi, A. Maguire, N.T. Pottackal, M.S.H. Thakur, M.M. Ikram, A.J. Hart, P. M. Ajayan, M.M. Rahman, Direct ink writing: A 3D printing technology for diverse materials, Adv. Mater. 34 (2022) 2108855, https://doi.org/10.1002/adma.202108855.
[110] C. Gao, Q. You, J. Huang, J. Sun, X. Yao, M. Zhu, Y. Zhao, T. Deng, Ultraconformable integrated wireless charging micro-supercapacitor skin, Nano Micro Lett. 16 (2024) 123, https://doi.org/10.1007/s40820-024-01352-1.
[111] Y. Wang, H. Haick, S. Guo, C. Wang, S. Lee, T. Yokota, T. Someya, Skin bioelectronics towards long-term, continuous health monitoring, Chem. Soc. Rev. 51 (2022) 3759–3793, https://doi.org/10.1002/adma.202108855.
[112] S. Hongwei, J. Li, W. Qi, Z. Zongwen, L. Yurong, M. Hongyun, B. Huasheng, Y. Jiao, S. Mingjiao, L. Fengfeng, A soft implantable energy supply system that integrates wireless charging and biodegradable Zn-ion hybrid supercapacitors, Sci. Adv. 9 (2023) 8083, https://doi.org/10.1126/sciadv.adh8083.
[113] A.E. Ostfeld, A.M. Gaikwad, Y. Khan, A.C. Arias, High-performance flexible energy storage and harvesting system for wearable electronics, Sci. Rep. 6 (2016) 26122, https://doi.org/10.1038/srep26122.
[114] Z. Liu, F. Mo, H. Li, M. Zhu, Z. Wang, G. Liang, C. Zhi, Advances in flexible and wearable energy-storage textiles, Small Methods 2 (2018) 1800124, https://doi.org/10.1002/smtd.201800124.
[115] S. Iqbal, N.F. Alshammari, M. Shouran, J. Massoud, Smart and sustainable wireless electric vehicle charging strategy with renewable energy and Internet of things integration, Sustainability 16 (2024) 2487, https://doi.org/10.3390/su16062487.
[116] S.M. Iqbal, I. Mahgoub, E. Du, M.A. Leavitt, W. Asghar, Advances in Healthcare Wearable Devices, npj Flexible Electron. 5 (2021) 9, https://doi.org/10.1038/s41528-021-00107-x.
[117] D. Zhang, T. Huang, L. Duan, Emerging self-emissive technologies for flexible displays, Adv. Mater. 32 (2020) 1902391, https://doi.org/10.1002/adma.201902391.
[118] A.S. Moursi, N. El-Fishawy, S. Djahel, M.A. Shouman, An IoT enabled system for enhanced air quality monitoring and prediction on the edge, Complex Intell. Syst. 7 (2021) 2923–2947, https://doi.org/10.1007/s40747-021-00476-w.
[119] Y. Xiong, D. Zhang, X. Ruan, S. Jiang, X. Zou, W. Yuan, X. Liu, Y. Zhang, Z. Nie, D. Wei, Artificial intelligence in rechargeable battery: advancements and prospects, Energy Storage Mater (2024) 103860, https://doi.org/10.1016/j.ensm.2024.103860.
[120] Z. Nie, W. Yan, X. Han, H. Yu, Y. Zhang, M. Tian, X. Zhang, Y. Xiong, P. Cao, G. Zhang, Damage-free non-mechanical transfer strategy for highly transparent, stretchable embedded metallic micromesh electrodes, Composites, Part B 289 (2025) 111934, https://doi.org/10.1016/j.compositesb.2024.111934.
[121] T. Yu, C. Wang, H. Yang, F. Li, Machine learning in metal-ion battery research: Advancing material prediction, characterization, and status evaluation, J. Energy Chem. 90 (2024) 191–204, https://doi.org/10.1016/j.jechem.2023.10.049.

Weiwei Zhao is an associate professor in State Key Laboratory of Flexible Electronics (LoFE) & Institute of Advanced Materials (IAM), Nanjing University of Posts & Telecommunications. She obtained her Ph.D. degree from Tianjin University in 2015. Her research mainly focuses on design and synthesis of two-dimensional nanomaterials for flexible devices.

Qiang Zhao obtained his Ph.D. from Fudan University in 2007. He then became a postdoctoral fellow at Nagoya University of Japan. He joined State Key Laboratory of Flexible Electronics (LoFE) & Institute of Advanced Materials (IAM), Nanjing University of Posts & Telecommunications in 2008. Since 2010, he has been a full professor. His research interests focus on the design and synthesis of flexible photoelectron materials and devices.