

MXene Nanosheet-enhanced Ionotronic Hydrogels for Wireless Powering and Noncontact Sensing

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 Electronic Supplementary Information

Abstract Smart actuators and wearable and implantable devices have attracted much attention in healthcare and environmental sensing. Flexible electronic and ionic materials are the two main approaches used to construct these devices. Among them, hydrogel-based ionic materials offer unique advantages, such as biocompatibility and adaptable mechanical properties. However, ionic hydrogels encounter challenges in achieving wirelessly powered and noncontact sensing. To address this, we introduce MXene nanosheets to construct ionotronic hydrogels. Leveraging the rich surface charges and electronic conductivity of MXene nanosheets, ionotronic hydrogels can harvest vibrational and electromagnetic waves as electrical energy and enable noncontact sensing. Under ultrasound, it can continuously generate voltages up to 85 V and light up light-emitting diodes, promising wireless charging of implanted devices. In addition, it achieves an absorption coefficient of 0.2 for 915 MHz electromagnetic waves, enabling noncontact sensing through radio frequency identification. Notably, the physically crosslinked network of the MXene-based hydrogels maintained structural and performance stability under ultrasonic stimulation and exhibited self-healing properties. Even when cut into two halves, the self-healing hydrogel fully regenerates its original performance. This study provides insight into the development of ionotronic hydrogels for wirelessly powered and noncontact sensing in smart actuators and wearable and implantable applications.

Keywords Hydrogels; Ionotronics; MXene nanosheets; Energy harvesting; Noncontact sensing

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INTRODUCTION

Smart actuators and wearable and implantable devices for healthcare and environmental sensing have received considerable attention in recent years.^[1–6] Flexible electronic and ionic materials are the two main approaches used to construct these devices.^[7–11] Among them, ionic hydrogels offer unique advantages, such as biocompatibility and adaptable mechanical properties.^[12–16] However, ionic hydrogels face challenges in achieving wirelessly powered and noncontact sensing. Existing energy conversion methods, including thermoelectric,^[17] humidity-driven,^[18] and piezoelectric techniques,^[19,20] suffer from low voltage outputs, typically less than 1 V, which is insufficient for power actuators and monitoring devices.^[21] In addition, noncontact sensing methods have limitations and often involve complex and less efficient mechanisms.

Fortunately, hydrogels, which have a composition similar to skin tissue, exhibit low acoustic impedance and high penetra-

tration depth, making them suitable for ultrasound-powered wireless implantable devices.^[22,23] Compared with thermoelectric and moisture-electric technologies, ultrasound energy harvesting offers more stable and efficient subcutaneous energy stimulation. Ultrasound-driven energy harvesting has emerged as a safe and effective method for wirelessly powering implantable medical devices capable of generating voltage outputs in the range of tens of volts.^[24–28] On the other hand, radio frequency identification (RFID) technology, which enables wireless data exchange via electromagnetic waves, is a promising approach for noncontact sensing.^[29–31] Integrating the efficient use of vibration and electromagnetic waves for wireless power and noncontact sensing could lead to more integrated and efficient systems. However, existing hydrogels primarily rely on simplex ionic or electronic conductivity, leading to insufficient sensitivity to vibrational and electromagnetic waves. The development of ionotronic hydrogels with dual ionic and electronic carriers offers a promising solution to this issue.^[24,32–34]

Here, we present MXene nanosheets for the construction of ionotronic hydrogels. By utilizing the rich surface charge and electronic conductivity of MXene nanosheets,^[32,34–37] the generated streaming vibration potential (SVP) in ionotronic hydrogels enables the conversion of ultrasonic energy into

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electrical energy, resulting in a high output voltage for wireless power supply. Moreover, the inherent high conductivity of MXenes makes ionotronic hydrogels suitable for electromagnetic wave communication, enabling noncontact information transmission with high sensitivity and real-time response. In addition, ionotronic hydrogels exhibit excellent self-healing properties and flexibility, making them ideal for use as actuators and wearable and implantable devices. This work proposes a feasible strategy for creating highly integrated, durable, and easily moldable wirelessly powered and non-contact sensing devices.

EXPERIMENTAL

A detailed Experimental Section can be found in the electronic supplementary information (ESI).

RESULTS AND DISCUSSION

Design of the Ionotronic Hydrogels

The structural design of the hydrogel is illustrated in Fig. 1(a). The carboxyl groups ($-\text{COOH}$) of poly(acrylic acid) (PAA) chelate with Ca^{2+} ions from amorphous calcium carbonate (ACC), forming a soft, malleable, and self-healing hydrogel matrix. MXene, a two-dimensional nanosheet with rich terminal groups and metallic conductivity, further enhances the mechanical and ionotronic properties of the hydrogel. The introduction of MXene nanosheets provides ionotronic hydrogels with abundant negatively charged groups. This facilitates charge migration and accumulation within the hydrogel, enabling the conversion of ultrasonic and electromagnetic wave energy into electrical energy. Therefore, we incorporated MXene nanosheets, ranging from 200 nm to 600 nm in width

and 5 nm in thickness, into the PAA/ACC matrix (see Figs. S1 and S2 in ESI). Its high specific surface area provides an abundance of electronegative terminal groups (such as $-\text{F}$, $-\text{OH}$, $-\text{O}$, and $-\text{Cl}$). These groups can engage in synergistic supramolecular interactions with PAA and Ca^{2+} ions, forming a dynamic physical entanglement network. The three-dimensional interconnected network of the hydrogel is also evident in the scanning electron microscopy (SEM) images (Fig. S3 in ESI). This dynamic physical entanglement network imparts excellent mechanical adaptability to the hydrogel. The ionotronic hydrogel is soft and highly stretchable (Fig. S4 in ESI). The hydrogel is easily molded into various shapes, such as cups, flowers, butterflies, and stars (Fig. 1b). Furthermore, owing to its dynamic network, the hydrogel exhibited outstanding self-healing properties. After the hydrogel is cut into four pieces, the application of external force enables rapid restoration to its original shape, without any visible cracks or other changes (Fig. 1c). This demonstrates that the mechanical performance of the ionotronic hydrogel after healing is nearly indistinguishable from its original state, with negligible damage. The observed self-healing ability of the ionotronic hydrogel can be explained by the synergistic supramolecular interactions among the PAA chains, Ca^{2+} ions, and groups on the MXene nanosheets. Upon recontacting the fractured samples, the synergistic supramolecular interactions promote chain diffusion and re-entanglement at the fractured interface, resulting in the reformation of a new, intact physically crosslinked network. Additionally, external pressure accelerates the formation of an intact physically crosslinked network. When completely dried, the hydrogel becomes rigid and tough. Upon rehydration, it recovers its original soft and stretchable properties, demonstrating the excellent recyclability of the hydrogel (Fig. S5 in ESI).

Rheological tests were subsequently employed to scruti-

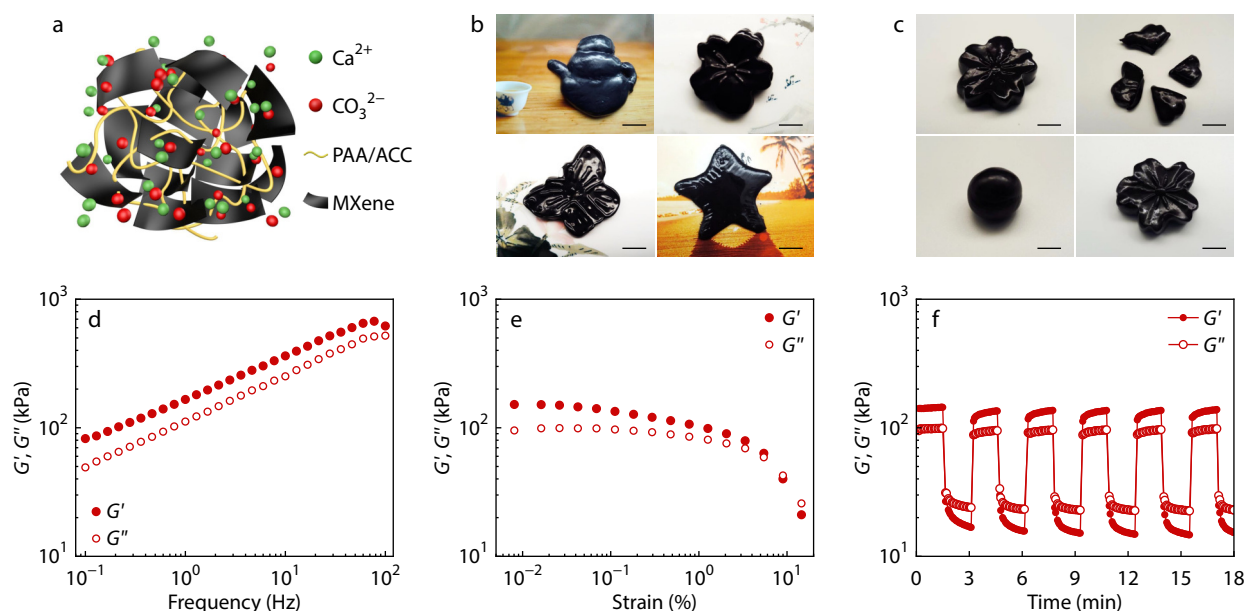


Fig. 1 Mechanical properties of the ionotronic hydrogel. (a) Schematic illustration of the dynamically crosslinked structure of the ionotronic hydrogel; (b) The ionotronic hydrogel can be shaped into a cup, a flower, a butterfly, or a star (scale bar: 1 cm); (c) Photos indicating the self-healing ability of the ionotronic hydrogel (scale bars: 1 cm); (d) Frequency dependency of the storage (G') and loss (G'') moduli of the ionotronic hydrogel; (e) Strain sweeping of the ionotronic hydrogel from 0.01% to 10% strain; (f) Continuous step-strain oscillatory measurements of the ionotronic hydrogel from 10% to 0.1% and back to 10% strain.

nize the influence of MXenes on the dynamic physical network of the hydrogel. The addition of MXene could tailor the mechanical properties of the ionotronic hydrogel (Fig. S6 in ESI). Without the addition of MXene nanosheets, the loss modulus (G'') and storage modulus (G') of the PAA/ACC hydrogel significantly differ at low frequencies. At an MXene content of 2 wt%, G'' surpasses G' in the low-frequency range, indicating the characteristics of a viscoelastic fluid. When the MXene content reaches 6 wt%, the ionotronic hydrogel displays an equal storage modulus (G') and loss modulus (G'') within the low-frequency range. At a 10 wt% MXene content, the ionotronic hydrogel has $G' > G''$ across the entire frequency range, indicating characteristics akin to those of an elastic solid (see Fig. 1d). However, excess MXene nanosheets make the hydrogel brittle. Therefore, the ionotronic hydrogel with a 10 wt% MXene content was selected as the optimal sample for subsequent tests and applications.

Under low-amplitude oscillation ($\gamma < 7\%$), G' is greater than G'' , demonstrating that the hydrogel behaves as an elastic solid. Strain sweep measurements ranging from 0.01% to 10% revealed that at $\gamma = 7\%$, G' equaled G'' , indicating the onset of a gel-sol transition.^[38] Under high-amplitude oscillation ($\gamma > 7\%$), G' is lower than G'' , implying that the crosslinked network is disrupted at high amplitudes (Fig. 1e). However, during continuous step-strain testing, alternating between amplitudes of 0.1% and 10%, G' and G'' could promptly recover over 98%. Even after multiple cycles, the ionotronic hydrogel exhibited excellent self-healing behavior. This suggests that the crosslinked network of the ionotronic hydrogel can be continuously disrupted and reshaped in a short period, resulting in outstanding self-repair capabilities (Fig. 1f). Moreover, the apparent activation energy of the physically crosslinked network was calculated from the Arrhenius equation, which is $135.3 \text{ kJ}\cdot\text{mol}^{-1}$ (Fig. S7 in ESI), comparable to that of many tough and self-healing hydrogels.

Wirelessly Powering through Ultrasonic Waves

When subjected to ultrasonic waves (Figs. 2a and 2b), the ionotronic hydrogel generates an open-circuit voltage of approximately 85 V at a frequency of 22 kHz and a power of 6.5 W (Fig. 2c). Under high-intensity ultrasound, the hydrogel can stably output electrical energy. The ionotronic hydrogel maintains its physical integrity and no noticeable damage to the hydrogel is observed after ultrasonic stimulation (Fig. S8 in ESI). Remarkably, the sinusoidal waveform of the voltage generated by the hydrogel at 22 kHz perfectly matches the ultrasonic wave frequency (Fig. 2d), confirming that the electrical energy is derived from ultrasonic energy conversion. Additionally, the ionotronic hydrogel has a high conductivity of up to $2 \text{ S}\cdot\text{m}^{-1}$, whereas the conductivity of the PAA/ACC hydrogel without MXene nanosheets is only $0.2 \text{ S}\cdot\text{m}^{-1}$. The conductivity of the PAA/ACC hydrogel increases with the addition of MXene nanosheets (Fig. 2e, Figs. S9 and S10 in ESI). At the same ultrasound intensity, the hydrogel with a higher MXene content shows a significant increase in the output voltage. This occurred because the addition of MXene nanosheets increases the density of ionic groups within the hydrogel, confirming the necessity of ionotronic MXene nanosheets for high-voltage generation (Figs. S11 and S12 in ESI). However, excessive MXene nanosheets result in increased stiffness and brittleness of the hydrogels. Therefore, 10

wt% MXene nanosheets were chosen for the subsequent experiments. The output voltage of the ionotronic hydrogel was measured in air, pork, water, and coupling media (Figs. 2f–2h). Notably, in air, substantial voltage attenuation is observed. With an air gap of only 100 μm , the voltage decreases to 20 V. As the gap further increases, reaching 300 μm , the output voltage is 9 V (Fig. 2f and Fig. S13 in ESI). This is attributed primarily to significant ultrasonic wave attenuation in air, resulting in the low ultrasonic wave energy received by the ionotronic hydrogel. In contrast, in pork, the voltage exhibits minimal variation. Even with an 8 cm-thick pork layer, the output voltage was maintained at 61 V (Fig. 2g and Fig. S14 in ESI), indicating its promising application in biological tissues. Across water, coupling agent, and polyacrylamide (PAM) hydrogel media, the attenuation of the output voltage is small, which is only approximately 30% in the coupling agent and PAM hydrogel (Fig. 2h and Fig. S15 in ESI). The output voltage of ionotronic hydrogels varies across different media, which is attributed primarily to the varying degrees of acoustic impedance mismatch between different media interfaces.^[39] These observations underscore the influence of different media on the output voltage of the ionotronic hydrogel, demonstrating its versatility and effectiveness in various environmental conditions. Moreover, the short-circuit current of the ionotronic hydrogel reached approximately 1.4 μA (Fig. 2i). Then, we conduct tests under varying external resistances to evaluate the output voltage (Fig. 2j and Fig. S16 in ESI) and output current (Fig. 2k and Fig. S17 in ESI). The output power reaches an impressive 85 μW with an external resistance of 0.01 $\text{M}\Omega$ (Fig. 2l). When the input power of the ultrasonic waves is 6.5 W, the U_{max} is about 89 V (Fig. S18a in ESI). Therefore, the η is calculated to be 3.05 %. When the input power of the ultrasonic waves increases to 65 W, the U_{max} increases slightly to 100 V (Fig. S18b in ESI), while the η decreases to 0.38%. These findings underscore the potential of ionotronic hydrogels as promising candidates for use as implantable power sources within the human body.

Energy Harvesting to Charge Electronics

When MXene nanosheets were embedded in the hydrogel, they introduce many electrical double layer (EDL) interfaces in the hydrogel. Ultrasonic waves drive the cations at the EDL interface to move along the direction of wave propagation. This leads to the exposure of negatively charged surfaces of the MXene nanosheet. To maintain charge balance in the EDL, electrons in the MXene nanosheets flow towards an external grounded electrode. It thus creates a potential difference in the direction of ultrasonic wave propagation. This potential difference is known as the streaming vibration potential (SVP).^[24] Since the ultrasonic wave is periodic, the pressure applied to the hydrogel is intermittent. During the absence of pressure, the cations return to their original positions, and the electrons flow back to restore charge balance. This cyclical process repeats with each passing ultrasonic wave, causing the electrons to oscillate through the external circuit between the MXene nanosheets and the grounded electrode, generating alternating voltage and current (Fig. 3a).

To validate the potential of ionotronic hydrogels as clean generators that efficiently convert ultrasonic wave energy into electrical power with high output, we design a circuit diagram and demonstrate various applications (Fig. 3a). The

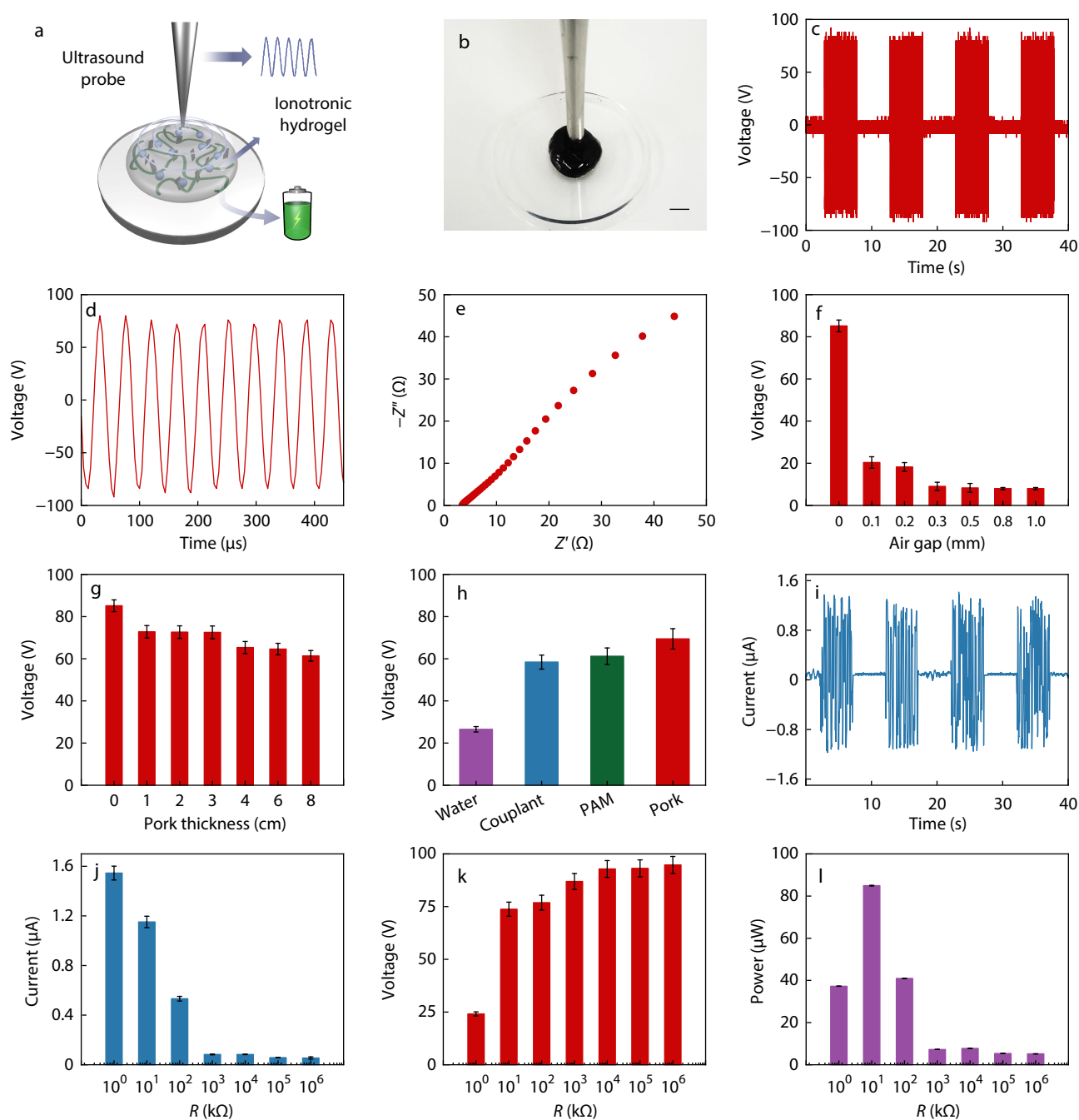


Fig. 2 Electrical generation by ultrasonic propagation in the ionotronic hydrogel. The ultrasonic power used is 6.5 W. (a) Schematic illustration of harvesting ultrasonic energy into electrical energy by the ionotronic hydrogel; (b) A photo showing the testing setup with the ionotronic hydrogel in contact with the ultrasonic probe (scale bar: 2 cm); (c) Output voltages of the ionotronic hydrogel stimulated by ultrasonic energy with a power of 6.5 W and a frequency of 22 kHz; (d) Local magnified data from (c); (e) Impedance spectrum of the ionotronic hydrogel with 10 wt% MXene; (f) Statistic output voltages of the ionotronic hydrogel measured with different air gaps between the ultrasonic probe and the hydrogel; (g) Statistic output voltages of the ionotronic hydrogel with different thicknesses of the pork medium; (h) Statistic output voltages of the ionotronic hydrogel with different media between the ultrasonic probe and the hydrogel; (i) Short-circuit currents of the ionotronic hydrogel; (j) Statistic output currents of the ionotronic hydrogel with different load resistances; (k) Statistic output voltages of the ionotronic hydrogel with different load resistances; (l) Statistic output powers of the ionotronic hydrogel with different load resistances.

ionotronic hydrogel generator, before rectification, could directly generate an alternating voltage of 85 V, which reached a direct voltage of up to 120 V after rectification (Fig. 3b). The alternating voltage generated by the ionotronic hydrogel

lights an electroluminescent device. The electroluminescent device emitted a stable blue light, demonstrating that the ionotronic hydrogel can sustainably provide high voltage (Fig. S19 in ESI). After ultrasonic wave energy is converted in-

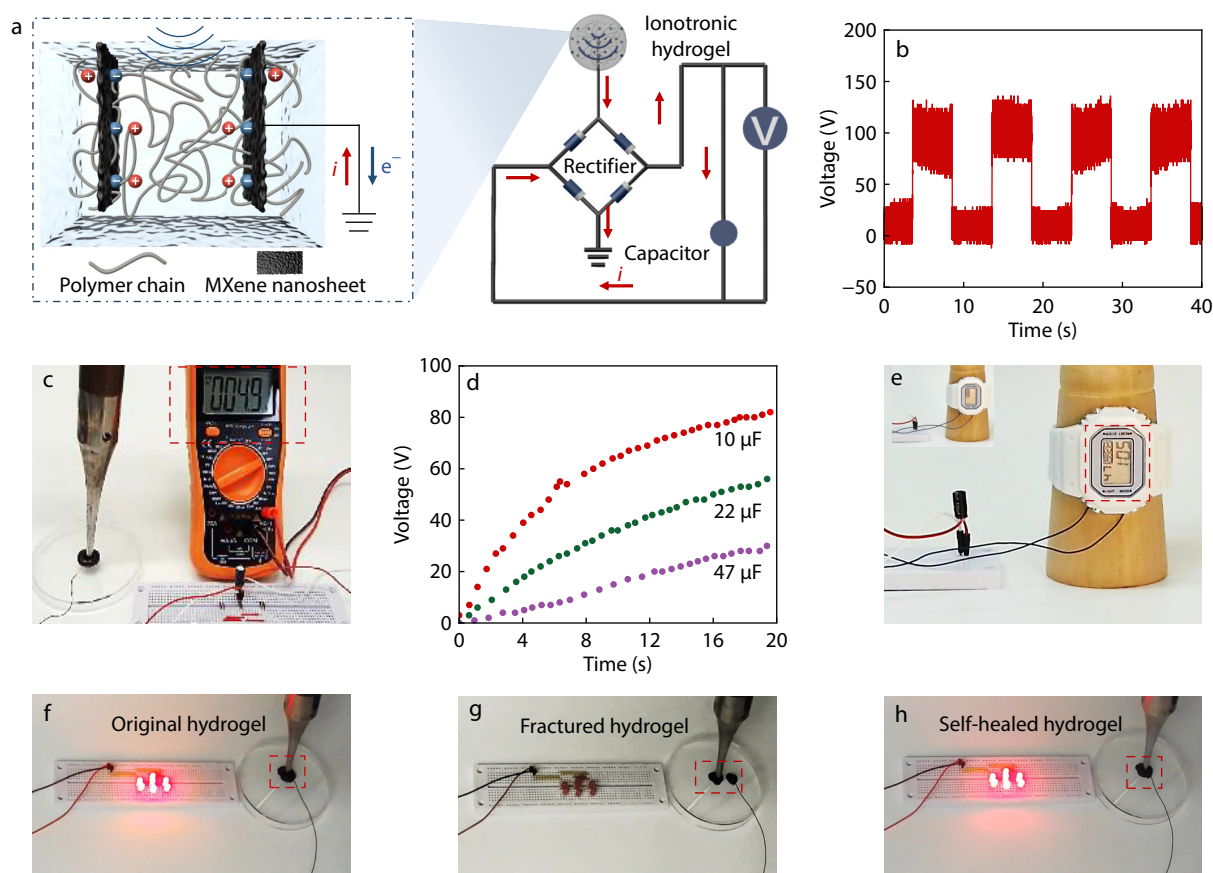


Fig. 3 Applications of the ionotronic hydrogel. (a) Schematic illustration of the mechanism for voltage generation in the ionotronic hydrogel and circuit design for wireless powering; (b) Rectified voltage output of the ionotronic hydrogel; (c) A photo showing the process of harvesting ultrasonic energy to charge a capacitor; (d) Charging curve of different capacitors; (e) A photo showing that the charged capacitor could support a smartwatch running; (f) A photo showing the original ionotronic hydrogel directly harvesting ultrasonic energy into electricity to light LEDs; (g) A photo showing the fractured hydrogel unable to light LEDs; (h) A photo showing the self-healed ionotronic hydrogel harvesting ultrasonic energy into electricity to light LEDs.

to electrical power, the ionotronic hydrogel is capable of rapidly charging capacitors. When a 10 μF capacitor is charged, the ultrasonic wave-driven ionotronic hydrogel can charge it to 83 V within 20 s (Figs. 3c and 3d, Video S1 in ESI). For capacitors with capacities of 22 and 47 μF , the voltages after 20 s of charging are 58 and 36 V, respectively. When a 10 μF capacitor charged for 20 s is used as a power source, its high direct current voltage (83 V) can drive various electronic devices. For example, it can be connected to a smartwatch, enabling its successful operation (Fig. 3e, Video S1 in ESI). In addition, the ionotronic hydrogel self-heals during energy harvesting and charging. The original ionotronic hydrogel exposed to ultrasonic waves can illuminate light-emitting diodes (LEDs) (Fig. 3f, Video S2 in ESI). After the ionotronic hydrogel was cut into two halves, the LEDs were turned off (Fig. 3g). However, when the broken parts of the ionotronic hydrogel come into contact, the LEDs are instantly lit again (Fig. 3h). This is attributed to the excellent self-healing performance conferred by the dynamic physical cross-linking network of the ionotronic hydrogel. Therefore, ionotronic hydrogels can not only harvest wave energy into electricity but also have potential for long-term stable and durable operation in practical applications.

Underwater Noncontact Sensing

Through the conversion of acoustic energy into electrical power, ionotronic hydrogels can be engineered into self-powered underwater detectors for tasks such as underwater sonar detection and source localization (Fig. S20 in ESI). Leveraging the propagation of ultrasound underwater, the ionotronic hydrogel can receive ultrasound signals, enabling the monitoring of underwater object movements and facilitating a deeper understanding of submerged environments. It swiftly captures ultrasound energy from various angles to rapidly generate voltage signals, which are then transmitted to a computer terminal for processing. When the ionotronic hydrogel is in the horizontal motion of the detector facing the ultrasound probe, the voltage signal linearly decreases with increasing distance (Fig. 4a, Figs. S21 and S22 in ESI). When the ionotronic hydrogel conducts circular motion (radius: 12 cm) around the ultrasonic probe, it generates a stable 65 V voltage signal (Fig. 4b, Figs. S23 and S24 in ESI). Furthermore, as the detector undergoes vertical motion relative to the ultrasound probe (horizontal distance is 8 cm), the voltage signal initially increases and then decreases with increasing detector-cylinder bottom distance (Fig. 4c, Figs. S25 and S26 in ESI). The ionotronic hydrogel excels in multidirectional underwater ultrasonic detection.

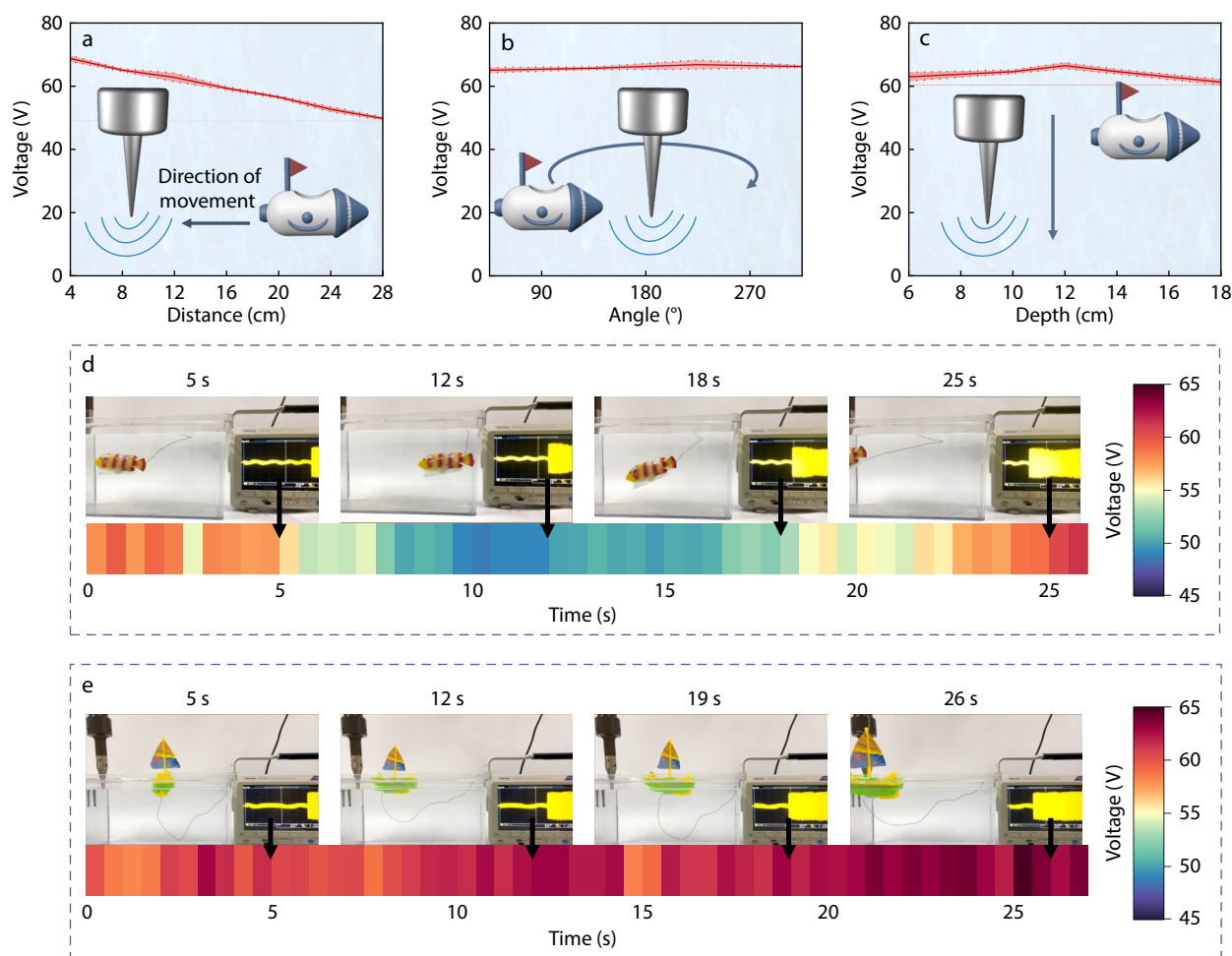


Fig. 4 Underwater noncontact sensing. The ultrasonic power used is 650 W. (a) Output voltage changes of the ionotronic hydrogel sensor at different distances from the ultrasonic probe; (b) Output voltage changes of the ionotronic hydrogel sensor at different angles to the ultrasonic probe; (c) Output voltages of the ionotronic hydrogel sensor moving to different depths below the water surface; (d) Output voltage changes of the ionotronic hydrogel monitoring the movement of a plastic fish. The hydrogel is attached to the plastic fish. (e) Output voltage changes of the ionotronic hydrogel monitoring the movement of a plastic boat. The hydrogel was attached to a plastic boat.

There is a decrease in the output voltage signal with increasing distance. These outputs of diverse voltage signals along different trajectories demonstrate that the ionotronic hydrogel detector achieves rapid and precise localization of the sound source, enabling real-time monitoring of underwater object movement. Real-time responsive output voltage signals are detected when a plastic fish with an attached detector swim. As the fish swims further away from the ultrasound source, the voltage signal diminishes. Conversely, as the fish swims toward the ultrasound source, the voltage signal increases, aligning with the initial voltage signal when the fish is close to the ultrasound source (Fig. 4d). This provides real-time feedback on the underwater position and movements of the fish. Similarly, when a plastic boat with an attached detector performs circular motion around the sound source, corresponding voltage signal responses are detected. As the plastic boat moves around the ultrasound source, maintaining a consistent distance from it, the subsequent change in the voltage signal is minimal (Fig. 4e). The ionotronic hydrogel thus demonstrates the capability for object localization and real-time detection in underwater environments, indicating significant potential applications in the

field of marine exploration.

Ionotronic Hydrogel Antennas for Radio Frequency Identification (RFID) Applications

The severe attenuation of ultrasonic waves in the air hinders their use as an energy stimulus source for sensors and prevents energy and information exchange in the air. However, ultrahigh-frequency (UHF) electromagnetic waves offer robust information exchange capabilities, compensating for the limitations of ultrasonic waves. The ionotronic hydrogel not only efficiently converts high-intensity acoustic energy into electrical energy but also captures UHF electromagnetic waves and converts them into electricity. This dual capability underscores its potential applications in fields such as high-frequency wireless communications. In addition, compared with their conventional metallic antennas and ink-based counterparts, ionotronic hydrogels exhibit outstanding self-healing and shape-adaptable properties. Hydrogel antennas hold promise for endowing electronic tags with superior tear resistance and enhanced flexibility.

To validate its ability to harvest UHF electromagnetic waves in air, an ionotronic hydrogel is used as an antenna to fabri-

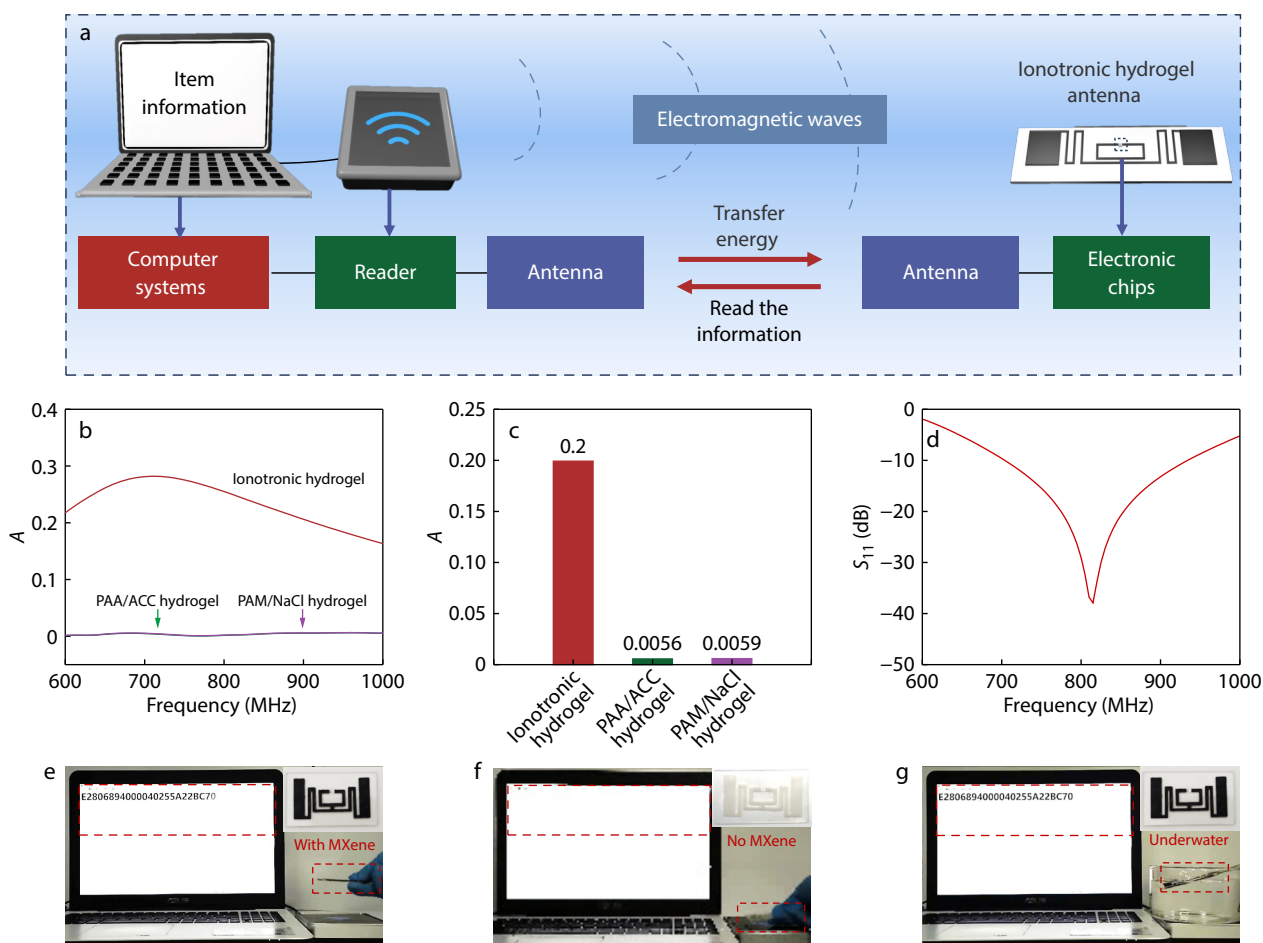


Fig. 5 Hydrogel antenna for RFID applications. (a) Schematic diagram of RFID application based on the ionotronic hydrogel antenna; (b) Absorption coefficient (A) of the ionotronic hydrogel, PAA/ACC hydrogel, and PAM/NaCl hydrogel; (c) Absorption coefficient of the ionotronic hydrogel, PAA/ACC hydrogel, and PAM/NaCl hydrogel at a frequency of 915 MHz; (d) S_{11} of the ionotronic hydrogel antenna; (e) Photo of the ionotronic hydrogel antenna and photograph showing it enabling information sensing and reading; (f) Photo of the hydrogel antenna without MXene nanosheets and photograph showing its failure in information sensing and reading; (g) Photo of the ionotronic hydrogel antenna and photograph showing it enabling underwater information sensing and reading.

cate electronic tags for RFID (Fig. 5a). The ionotronic hydrogel antenna receives the UHF electromagnetic wave energy emitted by the reader, converts it to electrical energy, and activates the electronic chip. The signal stored in the electronic chip is then converted into the corresponding electromagnetic wave signal, which is then transmitted to the reader. Finally, the reader receives the signal and transmits it to the computer terminal for processing. In the design of the tag antenna, the power reflection coefficient S_{11} of the antenna describes the power transfer ratio from the antenna to the chip.

MXene nanosheets exhibit strong interactions with electromagnetic waves, significantly enhancing the electromagnetic wave absorption capabilities of hydrogels when used as fillers.^[32,36,40] We characterized the electromagnetic wave absorption performance of the ionotronic hydrogel by testing its absorption coefficient (A).^[41] For comparison, we also tested PAA/ACC hydrogels and PAM/NaCl hydrogels without MXene nanosheets. Unlike the negligible absorbance of the control hydrogels, the ionotronic hydrogel exhibited an absorption coefficient of 0.16–0.28 in the frequency range of 600–1000 MHz (Fig. 5b), indicating significantly enhanced ab-

sorption of electromagnetic waves. Moreover, at the commonly used RFID frequency of 915 MHz, the ionotronic hydrogel achieves an electromagnetic wave absorption coefficient of 0.2 (Fig. 5c). The ionotronic hydrogel achieves an absorption coefficient of 0.2 at 915 MHz, with a maximum value of 0.28 at 710 MHz, outperforming the PAM hydrogel by 3280% and 5850% respectively. Therefore, the ionotronic hydrogel has the significant advantage of a higher absorption coefficient compared to conventional hydrogels.

On the other hand, flexible antennas made from ionotronic hydrogels enable wireless sensing and signal transmission with wearable electronics.^[30,31] Therefore, we fabricate an antenna from an ionotronic hydrogel tuned to respond to 915 MHz electromagnetic waves (Fig. S27 in ESI). The reflection coefficient S_{11} of the antenna is typically used to evaluate its performance. The S_{11} of the ionotronic hydrogel antenna remains below -10 dB across a broad frequency range of 690–935 MHz (Fig. 5d), indicating that the antenna could receive more than 90% of the electromagnetic wave energy input.^[29] Specifically, at a frequency of 915 MHz, the S_{11} of the ionotronic hydrogel antenna was -11.7 dB. This further

demonstrates the potential of ionotronic hydrogels as antennas for passive RFID tags.

The practical communication performance of the ionotronic hydrogel antenna is tested through reading electronic tag information in RFID applications. When the antenna receives ultra-high-frequency electromagnetic wave energy emitted by the reader, converts it into electrical energy, and activates the electronic chip. The stored signal in the electronic chip is then converted into a corresponding electromagnetic wave signal, which is transmitted back to the reader. Finally, the reader receives the signal and sends it to a computer terminal for processing. The ionotronic hydrogel antenna embedded with an electronic chip responsive to the 915 MHz frequency band was read by a reader emitting 915 MHz electromagnetic waves. The entire process is performed in real time. The ionotronic hydrogel electronic tags successfully allow the reader to retrieve corresponding information stored in the electronic chip, which is then processed via a computer (Fig. 5e). However, the hydrogel electronic tags lacking MXene nanosheets fail to elicit a response from the commercial reader (Fig. 5f). These findings demonstrate that the addition of MXene nanosheets effectively enhances the interaction of the hydrogel antenna with electromagnetic waves, enabling the application of ionotronic hydrogel antennas in RFID. Moreover, when placed in water, the ionotronic hydrogel tags display even higher sensitivity, indicating their efficacy in energy harvesting and communication in both underwater and air environments (Fig. 5g). This also confirms the stability of the ionotronic hydrogel in aqueous environments.

Notably, conventional antennas typically employ metal materials to convert sound energy into electrical power. However, once damaged, they are challenging to repair. Conversely, ionotronic hydrogel antennas exhibit remarkable self-healing capabilities (Fig. S28 in ESI). When subjected to external damage, the ionotronic hydrogel tags initially fail to trigger a response from the reader (Fig. S29 in ESI) but can swiftly recover within 1–2 s. Compared with undamaged tags, self-healing tags can still be sensitively detected by the reader at approximately 3–4 cm, with no compromise in performance (Fig. S30 in ESI). This underscores its great potential to serve as a robust antenna for electronic tag fabrication.

Therefore, ionotronic hydrogel antennas effectively transmit information via RFID technology on the basis of electromagnetic wave conversion principles. This position has vast application prospects for the Internet of Things (IoT), including real-time sensing, identity recognition, and near-field communication, as well as mobile communication systems, large-scale data transmission, and high-volume information exchange scenarios.

CONCLUSIONS

In summary, this work develops physically cross-linked ionotronic hydrogels that utilize the rich surface charges and electronic conductivity of MXene nanosheets to harvest energy from ultrasonic and electromagnetic waves, enabling wirelessly powered and noncontact sensing. When stimulated by ultrasound, the hydrogel can continuously generate a voltage of up to 85 V, which is sufficient to light LEDs and has the potential for wireless powering of implantable devices. Ionotronic hydrogels

can also sense ultrasound to monitor the position and movement of underwater objects in real time. In addition, the ionotronic hydrogel antenna achieves a reflection coefficient of -11.7 dB at 915 MHz electromagnetic waves, enabling noncontact sensing via RFID technology. Importantly, the physically cross-linked network of the ionotronic hydrogel maintains its structural and performance stability under ultrasonic stimulation and exhibits self-healing properties. Even when cut in half, the self-healing hydrogel can fully recover its original performance. This research provides valuable insights for the development of hydrogel-based wireless power and noncontact sensors suitable for smart actuators and wearable and implantable devices.

Conflict of Interests

The authors declare no interest conflict.

Electronic Supplementary Information

Electronic supplementary information (ESI) is available free of charge in the online version of this article at <http://doi.org/10.1007/s10118-025-3253-6>.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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