Transient Batteries: A Promising Step towards Powering Green Electronics

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Abstract: Transient electronics is an emerging class of innovative technology wherein electronic devices undergo controlled degradation processes after a period of stable operation, leaving no toxic products behind. This technology offers exciting opportunities in research areas of green electronics, temporary biomedical implants, data-secure hardware systems, and many others. However, one major challenge with these devices is their rigid and bulky batteries that contain toxic chemicals and are not at all degradable. So, to realize autonomous and self-sufficient transient electronics, the development of transient batteries is a pre-requisite. This review provides an overview of the advancements in the field of transient batteries, their materials, output performance, transience behavior, and a few potential applications.

Keywords: Degradability · Electrochemical performance · Transient battery · Transient electronics

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1. Introduction

Rapid technological progress in consumer electronics has profoundly affected people's lives and work. Electronic devices are designed to bring as much comfort as possible to their users. But another aspect of this rapid development is the generation of a large amount of electronic waste. The new consumer trends, faster obsolescence, and the advent of the Internet-of-Things have resulted in an unprecedented increase in household and industrial electronic waste. To quantify, the global waste from electrical and electronic equipment (WEEE) production is expected to increase from 53.6 Mt in 2019 to 74.7 Mt by 2030.[1] Moreover, in 2019, only 17.4% of this generated WEEE was recycled.[1] The whereabouts of the remainder pose serious environmental concerns as a large portion of it probably ends up in oceans or landfills, causing severe damage to our ecosystem.

So, an effective solution to this exacerbating problem is the development of electronics that can physically vanish at the end of their life in a controlled fashion. Such devices have recently emerged under the name of 'transient electronics': electronic devices that can undergo controlled degradation processes after a period of stable operation, leaving no toxic degradation products behind.[2] Such electronics would have a massive effect on a vast array of interesting applications, such as the development of waste-free technology wherein green electronics can simply degrade into the surroundings with minimum to no impact, thus addressing the environmental challenge.[3,4]

In addition, transient electronics offers new opportunities in biomedicine, such as a transient medical device that can be implanted inside the body to treat/diagnose a disease and after its function ends, it can disappear without requiring a second surgery. This can reduce the cost, potential risks, and chronic inflammation caused by the permanent device. Finally, this technology can be of great use in secure hardware systems, especially for military application as it can self-destruct on demand and prevent access to sensitive information to an enemy.

The practical applications of transient electronics are limited mainly by the slow growth of energy storage devices that also need to degrade within the designed lifetime of the device. Among different electrochemical energy storage systems such as capacitors, supercapacitors, batteries, and fuel cells, we are mostly interested in transient batteries. They are a stable source of energy supply and deliver high energy density with excellent energy conversion efficiency.[5] Transient batteries can be either primary batteries that are made for single-use applications or secondary batteries that can be recharged multiple times before degrading. The fundamental operation and structure of the transient batteries are similar to traditional batteries; they are also made up of positive and

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negative electrodes (denoted as cathode and anode, respectively), separator/electrolyte, current collectors, and packaging (Fig. 1). But unlike traditional batteries that are built to stay for a long period, transient batteries are the complete opposite. Accordingly, all their battery components need to be redesigned such that they can degrade after their stable operation but without compromising on the electrochemical performance. Notably, the programmed degradation of such batteries is desired to occur without causing any adverse biological or environmental effects.
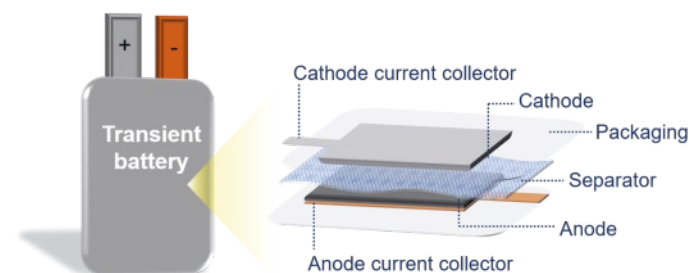

Fig. 1. Scheme of the typical structure of a transient battery, including both primary and secondary batteries.

To design and fabricate transient batteries, there is a scarcity of materials to choose from as it is mostly restricted to degradable, water-soluble, and nontoxic polymers, metals, and metal oxides. From this limited materials toolbox, one must be very careful in selecting the materials depending on the intended application of transient batteries. For consumer electronics, the degradability is aimed at reducing the contaminant accumulation in the environment and hence a partial disintegration is acceptable, as long as the end products are harmless. On the other hand, for batteries powering biomedical devices, biocompatibility is a must and complete disintegration is an essential requirement as non-degraded deposits may result in undesired biological responses.[6] The next critical challenge includes the development of new battery designs and fabrication methods that must satisfy completely different requirements than traditional batteries. And finally, the seamless integration of such batteries in functional transient devices is essential to make the transition from the laboratory to industry. In the following section, we present some key advances in the field of transient batteries, focusing on materials, full cell performance, transience behavior, and applications.

2. Green Materials for Transient Batteries

Transient primary batteries are typically galvanic cells built by combining two biocompatible metals with different electrochemical potentials. Biodegradable metals such as Mg, Mg alloys, Fe, Mo, W, Zn, but also metal oxides like MoO_3 are commonly employed electrode and current collector materials in primary batteries.[7,8] They possess the merits of excellent biocompatibility, low electronic resistance, acceptable degradation rates and harmless degradation products. These batteries release energy from the corrosion reaction of Mg anode and hydrogen evolution reaction (HER) on the cathode side.[9] To achieve better control over the corrosion reaction of Mg, different strategies are employed, such as alloying of Mg with other biocompatible metals,[10] coating its surface with biomaterials,[11] and optimizing its microstructure using different fabrication techniques.[12] On the cathode side, the release of hydrogen gas inside the human body, in some cases, can lead to blood clotting. So, replacing HER with oxygen reduction reaction (ORR) is more advantageous and this has been achieved using conductive polymers like polypyrrole and noble metals like Au as cathode materials (Fig. 2a).[13,14]
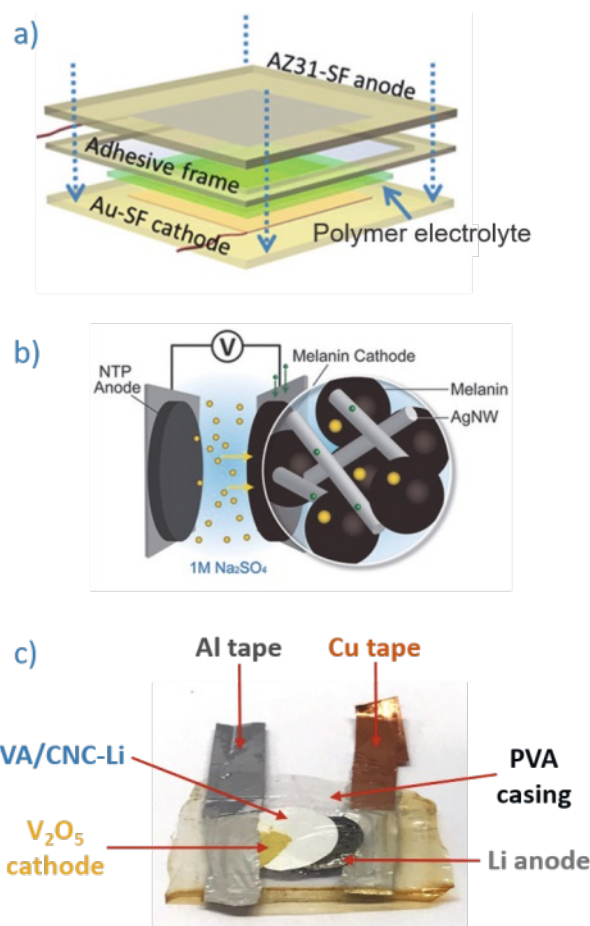

Fig. 2. Materials used in primary and secondary transient batteries: a) Schematic of a transient primary battery containing Mg alloy (AZ31) as an anode, gold nanoparticles deposited onto a silk film as a cathode, silk fibroin-ionic liquid polymer electrolyte, and a crystallized silk casing. Adapted with permission from the publisher from ref. [14]. Copyright 2017 American Chemical Society. b) Schematic illustration of a transient sodium-ion battery (NIB) containing sodium titanium phosphate as an anode and a composite cathode composed of melanin and silver nanowires operating in an aqueous electrolyte. Reproduced with permission from the publisher from ref. [15]. Copyright 2016 John Wiley and Sons. c) Optical photograph of a transient secondary lithium-ion battery (LIB) that contains Li metal as an anode, V_2O_5 nanofibers as cathode, PVA/cellulose nanocrystals-based separator soaked in ionic liquid as electrolyte, Al and Cu as current collectors, and PVA as packaging. Reproduced with permission from the publisher from ref. [18]. Copyright 2021 John Wiley and Sons.

Besides corrosion reactions, transient batteries that rely on the principle of reversibly binding to different metal ions like Na^+, Li^+ and Zn^{2+} have also been designed. Sodium-ion batteries (NIBs) utilize organic electrodes like activated carbon, biologically derived redox-active polymers such as polydopamine and melanin in addition to well-known metal oxides (Fig. 2b).[15–17] For developing rechargeable transient batteries, lithium-ion and zinc-ion chemistries (LIBs and ZIBs) are most exciting and the materials for these batteries are chosen considering their *ex vivo* applications. Lithium (Li) metal as anode and vanadium oxide (V_2O_5) as cathode are used in transient LIBs (Fig. 2c) because of their excellent dissolution behavior under aqueous conditions, a well-used trigger in transient electronics.[18] To boost the electrochemical performance of V_2O_5 cathode, many promising approaches such as use of origami design,[19] making paper-like electrodes,[20] and metal doping[21] are adopted that eventually provide higher capacity and good cyclability. In the case of ZIBs, cathode materials like MnO_2 and Prussian blue analogues are paired with Zn metal as anode.[22,23]

So far, we have only explored electrode materials and so now let us discuss the other three crucial battery components: the current collector that provides mechanical support to electrode materials and collects electrons from them; the separator soaked in a liquid electrolyte which physically separates anode and cathode while allowing ionic conduction between them; and the packaging that protects the entire battery from its surroundings. In the case of transient primary batteries, electrode materials also act as current collectors due to their excellent mechanical and electrical properties. And since these batteries are primarily designed to power implantable medical devices, body fluids are predestined to be electrolytes. For transient secondary batteries, including NIBs, LIBs and ZIBs, the current collectors are developed by depositing a thin layer of relatively inert metals like Cu, Al, and Ni onto degradable polymeric substrates, thus achieving a bilayer structure.[24] Additionally, synthesizing conducting polymer blends or composites by mixing conductive additives like Ag nanowires, carbon black, or graphene within a biodegradable polymer matrix is equally popular.[25] The conductivity and degradability of the blends are controlled by adjusting the proportion of conductive additive within the host matrix.

The electrolytes used in rechargeable transient batteries can be classified into organic electrolytes, aqueous electrolytes, ionic liquids, and polymer electrolytes.[26] The organic electrolyte is made up of a metal salt dissolved in carbonate solvents and added/infused into a porous separator, made up of water-soluble polymers like polyvinyl alcohol (PVA), polyvinylpyrrolidone (PVP), and polyethylene oxide (PEO) or naturally occurring polymers like cellulose and agarose.[18,19,24,27,28] As greener alternatives, aqueous electrolytes and ionic liquids are preferred, but they suffer from issues such as narrow electrochemical window, leakage, high cost, and volatilization.[26] Polymer electrolytes can solve the leakage and volatilization problems by confining the salt and solvent molecules within the degradable polymer matrix.[14]

The concept of transience relies on the clever design of packaging that provides a delicate balance between device operation lifetime and dissolution rate. It is desired that the packaging protects the inner battery components from the outside world, but at the same time, it is stable against the conditions present inside the battery and ultimately, it should be able to degrade after a stable operation. To date, few biodegradable polymers such as polyanhydrides, PVA, polylactide-co-glycoside (PLGA), sodium alginate (Na-AG), gelatin, silk and cellulose have been applied as casing materials for transient batteries.[9,14,16,18,24,25,29] The transience behavior of these polymers is directly related to their morphological, structural, and chemical features. By simply tuning the thickness, molecular weight, and crystallinity degree of encapsulant polymers, a more tailored and programmed degradation of batteries can be achieved. Their effectiveness can be further enhanced by employing a multilayer packaging strategy wherein a given polymer film is coated with different layers of metal oxides or other polymers that provide a particular advantage such as better waterproof or airproof properties.[30]

3. Full Cell Performance and Transience Behavior

A transient primary battery constructed by coupling 50 μm thick Mg foil as anode, 25 μm thick Mo foil as cathode, phosphate-buffered saline (PBS) as electrolyte and polyanhydride casing was reported by the Rogers group.[9] The battery delivered a low voltage of around 0.45 V for 24 h which was increased to 1.6 V by stacking the cells in series, sufficient to power a light-emitting diode (LED) and a wireless radio circuit. Its transiency was demonstrated in PBS solution at 37 °C during which the polyanhydride encasing degraded first, followed by a slow degradation of Mg and Mo foils for 11 days and then an accelerated dissolution of both foils in the next 8 days as the temperature of the solution was increased to 85 °C (Fig. 3a).
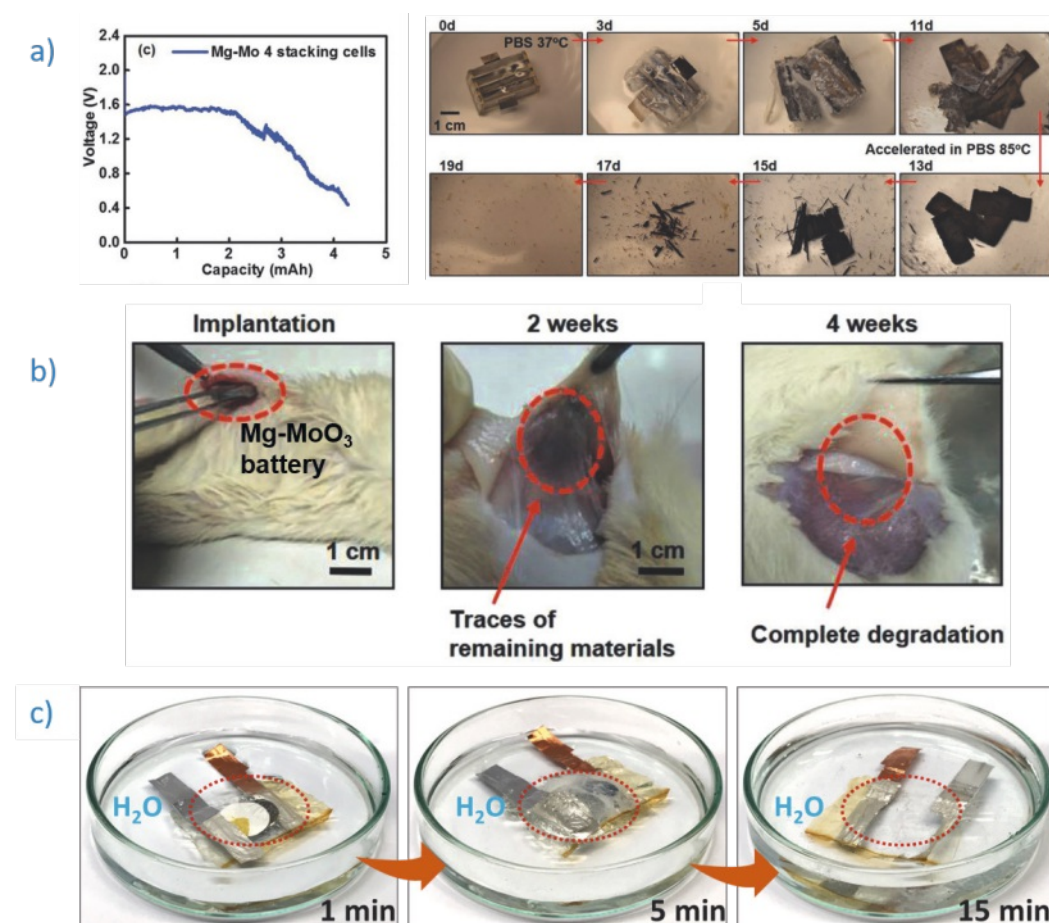

Fig. 3. Transience behavior in batteries. a) Left: discharging behavior of the Mg-Mo battery pack that contains four cells connected in series at a current density of 0.1 mA cm⁻². Right: optical images showing the degradation of the battery pack in phosphate-buffered saline at 37 °C and 85 °C. Reproduced with permission from the publisher from ref. [9]. Copyright 2014 John Wiley and Sons. b) Optical images showing *in vivo* degradation of Mg-MoO₃ battery in the subcutaneous area of rats at different time intervals. The complete degradation occurred within 4 weeks. Adapted with permission from the publisher from ref. [29]. Copyright 2018 John Wiley and Sons. c) Optical images showing the rapid degradation of a LIB in water at room temperature. Reproduced with permission from the publisher from ref. [18]. Copyright 2021 John Wiley and Sons.

To extend the battery lifetime from 24 h to 250 h while still achieving similar output voltage, Huang *et al.* developed a Mg-MoO_3 battery that contained alginate hydrogel electrolyte and polyanhydride /PLGA packaging.[29] The battery was shown to be fully degradable in PBS solution at 37 °C and 85 °C within 19 days and when implanted inside the subcutaneous area of Sprague-Dawley rats for *in vivo* degradation study, the battery showed no toxic effects and exhibited excellent biocompatibility (Fig. 3b). Both *in vitro* and *in vivo* tests confirm the feasibility of this battery technology and provide a critical step forward towards fabricating fully functional transient devices.

Despite the excellent biodegradability and decent electrochemical performance of the reported batteries, a particular challenge still exists in controlling the battery lifetime in accordance with implantable medical devices. As a solution, Jia *et al.* designed a silk-based thin film Mg battery using an anode composed of Mg alloy, Au nanoparticles deposited onto a silk film as a cathode, silk fibroin-ionic liquid polymer electrolyte and a crystallized silk casing.[14] The battery delivered a voltage above 1.21 V for 64 min under physiological conditions that was extended to 109 min by simply adding an extra layer of crystallized silk on top of the encapsulated battery. This result confirms that the degradation profile of batteries can be tuned by controlling the thickness or the number of layers of its casing material. Regarding the transiency, the battery was shown to be fully degraded after 45 days in buffered protease solution at 37 °C.

The Liangbing group demonstrated the first rechargeable transient LIB that consisted of Li and V_2O_5 electrodes, PVP separator soaked in organic electrolyte, thin films of Cu and Al deposited onto a Na-AG substrate as current collectors and Na-AG as packaging.[24] The battery delivered a working voltage of 2.8 V with a lifetime of 4 cycles and showed rapid dissolution in an aqueous solution. The degradation reaction occurred as follows: upon contact with water, the encapsulation and separator of the battery dissolved first, followed by the reaction of Li metal with water to produce a basic lithium hydroxide solution. The basic solution favored the dissolution of V_2O_5 and Al, resulting in the complete dissolution of the battery.

Recently, we reported a transient Li-V_2O_5 battery with similar transience concept but replaced the toxic organic electrolyte with a biocompatible ionic liquid.[18] By carefully designing and optimizing the ionic liquid–separator pair, the as-fabricated transient LIB can be cycled over 400 times and degraded in 15 min once an aqueous trigger was applied (Fig. 3c).

4. Towards Applications of Transient Batteries

Here we present a few inspiring examples of transient batteries that have been integrated into an electronic device and worked successfully. Recently, a fiber-shaped and rechargeable NIB was developed that consisted of a biodegradable fiber conductor coated with polydopamine/polypyrrole composite material as anode, MnO_2 as cathode, chitosan as separator and body fluid as electrolyte.[31] Due to its one-dimensional configuration and high flexibility, it could be easily injected into the body with minimal invasion. The fiber battery was shown to power a biosensor that detected pressure changes *in vivo* and then biodegraded within 10 weeks after completing its function. In another example, a stretchable and biodegradable Mg-Mo battery was designed to further extend the application of transient batteries to wearable electronics (Fig. 4a).[32] The battery showed good mechanical tolerance to bending and stretching while powering an electronic watch and wearable healthcare devices for pulsation sensing and low-noise surface electromyography applications (Fig. 4b,c). Importantly, the battery exhibited complete degradation in PBS/cellulase solution after 32 days, as shown in Fig. 4d. Lastly, a biocompatible Zn-Cu galvanic cell that used gastric fluid as electrolyte was reported to power a temperature sensor and wireless communication system located within the gastrointestinal tract of pigs for 6.1 days.[33]

4. Outlook

Transient batteries represent a step forward in developing greener alternatives to traditional batteries. Even though the field is growing slowly, we have already seen a few examples of fully functional electronic devices that are being powered by transient batteries. To boost further development in the field, it is necessary to design and synthesize new classes of biodegradable electronic components that can offer novel functionalities and degradation properties. In this regard, developing biopolymers that can undergo selective depolymerization back to their initial constituent's feedstock may offer exciting opportunities. Transient battery technology must focus on substituting individual battery components with abundant, environmentally safe, or biodegradable materials. Ideally, transiency can also be coupled with recycling to recover critical battery components if eco-friendly solutions are
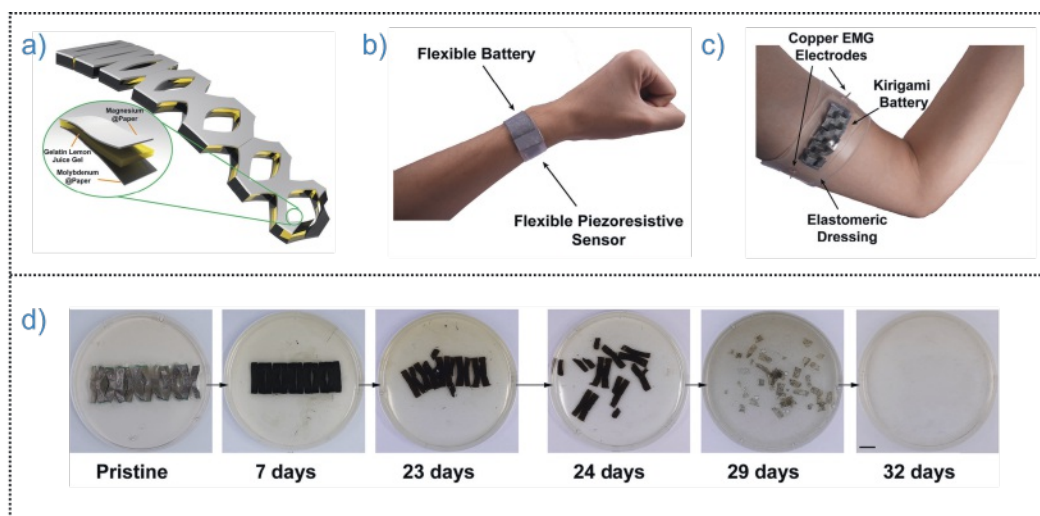

Fig. 4. An example of the potential applications of transient batteries. a) Schematic illustration of the kirigami pattern-inspired stretchable and degradable Mg-Mo battery. Optical images showing the integration of the Mg-Mo battery with b) a piezoresistive sensor as a wearable wristband and c) a wearable skin electromyography (sEMG) device attached to the human arm that contains two customized copper sEMG sensing electrodes and elastomeric dressing. d) Digital photographs showing the degradation of Mg-Mo battery in phosphate-buffered saline/cellulase solution for 32 days. The length of the scale bar is 1 cm. Reproduced with permission from the publisher from ref. [32]. Copyright 2021 The Hong Kong Polytechnic University and John Wiley and Sons, Australia.

not viable. Currently, the electrochemical and degradation performance of transient batteries are mostly measured *in vitro*. But the fundamental studies under *in vivo* conditions analyzing battery performance and its interaction with biotic systems like tissues are required. Similarly, for batteries powering eco-friendly electronics, it is critical to examine their environmental impact by studying their biodegradation processes using standardized tests. Further research efforts are required in device designs and fabrication methods to translate the technology to industry.

[1] V. Forti, C. P. Baldé, R. Kuehr, G. Bel, 'The Global E-Waste Monitor 2020: Quantities, Flows and the Circular Economy Potential', Bonn, Geneva, Rotterdam; **2020**.

[2] S. W. Hwang, H. Tao, D. H. Kim, H. Cheng, J. K. Song, E. Rill, M. A. Brenckle, B. Panilaitis, S. M. Won, Y. S. Kim, Y. M. Song, K. J. Yu, A. A. Ameen, R. Li, Y. Su, M. Yang, D. L. Kaplan, M. R. Zakin, M. J. Slepian, Y. Huang, F. G. Omenetto, J. A. Rogers, *Science* **2012**, *337*, 1640, https://doi.org/10.1126/science.1226325.

[3] I. Gomez, E. Lizundia, *Adv. Sustain. Syst.* **2021**, *5*, 2100236, https://doi.org/10.1002/adsu.202100236.

[4] K. K. Fu, Z. Wang, J. Dai, M. Carter, L. Hu, *Chem. Mater.* **2016**, *28*, 3527, https://doi.org/10.1021/acs.chemmater.5b04931.

[5] C. X. Zu, H. Li, *Energy Environ. Sci.* **2011**, *4*, 2614, https://doi.org/10.1039/c0ee00777c.

[6] E. Mariani, G. Lisignoli, R. M. Borzì, L. Pulsatelli, *Int. J. Mol. Sci.* **2019**, *20*, 636, https://doi.org/10.3390/ijms20030636.

[7] N. Mittal, A. Ojanguren, M. Niederberger, E. Lizundia, *Adv. Sci.* **2021**, *8*, 1, https://doi.org/10.1002/advs.202004814.

[8] L. A. Wehner, N. Mittal, T. Liu, M. Niederberger, *ACS Cent. Sci.* **2021**, *7*, 231, https://doi.org/10.1021/acscentsci.0c01318.

[9] L. Yin, X. Huang, H. Xu, Y. Zhang, J. Lam, J. Cheng, J. A. Rogers, *Adv. Mater.* **2014**, *26*, 3879, https://doi.org/10.1002/adma.201306304.

[10] M. M. Khan, Z. U. Rahman, K. M. Deen, I. Shabib, W. Haider, *Electrochim. Acta* **2020**, *329*, 135129, https://doi.org/10.1016/j.electacta.2019.135129.

[11] J. Xia, Z. Yuan, Z. F. J. Cai, *Mater. Eng. Perform.* **2018**, *27*, 4005, https://doi.org/10.1007/s11665-018-3512-6.

[12] M. Tsang, A. Armutlulu, F. Herrault, R. H. Shafer, S. A. B. Allen, M. J. Allen, *Microelectromechanical Syst.* **2014**, *23*, 1281, https://doi.org/10.1109/JMEMS.2014.2360201.

[13] X. Jia, C. Wang, C. Zhao, Y. Ge, G. G. Wallace, *Adv. Funct. Mater.* **2016**, *26*, 1454, https://doi.org/10.1002/adfm.201503498.

[14] X. Jia, C. Wang, V. Ranganathan, B. Napier, C. Yu, Y. Chao, M. Forsyth, F. G. Omenetto, D. R. Macfarlane, G. G. Wallace, *ACS Energy Lett.* **2017**, *2*, 831, https://doi.org/10.1021/acsenergylett.7b00012.

[15] Y. J. Kim, A. Khetan, W. Wu, S. E. Chun, V. Viswanathan, J. F. Whitacre, C. J. Bettinger, *Adv. Mater.* **2016**, *28*, 3173, https://doi.org/10.1002/adma.201504650.

[16] Y. J. Kim, S. E. Chun, J. Whitacre, C. J. Bettinger, *J. Mater. Chem. B* **2013**, *1*, 3781, https://doi.org/10.1039/c3tb20183j.

[17] T. Sun, Z. J. Li, H. G. Wang, D. Bao, F. L. Meng, X. B. Zhang, *Angew. Chem. Int. Ed.* **2016**, *55*, 10662, https://doi.org/10.1002/anie.201604519.

[18] N. Mittal, A. Ojanguren, N. Cavasin, E. Lizundia, M. Niederberger, *Adv. Funct. Mater.* **2021**, *31*, 2101827, https://doi.org/10.1002/adfm.202101827.

[19] K. Fu, Z. Wang, C. Yan, Z. Liu, Y. Yao, J. Dai, E. Hitz, Y. Wang, W. Luo, Y. Chen, M. Kim, L. Hu, *Adv. Energy Mater.* **2016**, *6*, 1, https://doi.org/10.1002/aenm.201502496.

[20] Z. Liu, K. Fu, Z. Wang, Y. Zhu, J. Wan, Y. Yao, J. Dai, M. Kim, L. Swafford, C. Wang, L. Hu, *Inorg. Chem. Front.* **2016**, *3*, 681, https://doi.org/10.1039/c5qi00288e.

[21] Z. Wang, K. K. Fu, Z. Liu, Y. Yao, J. Dai, Y. Wang, B. Liu, L. Hu, *Adv. Funct. Mater.* **2017**, *27*, 1605724, https://doi.org/10.1002/adfm.201605724.

[22] Z. Liu, G. Pulletikurthi, F. Endres, *ACS Appl. Mater. Interfaces* **2016**, *8*, 12158, https://doi.org/10.1021/acsami.6b01592.

[23] J. Zhou, Y. Li, L. Xie, R. Xu, R. Zhang, M. Gao, W. Tian, D. Li, L. Qiao, T. Wang, J. Cao, D. Wang, Y. Hou, W. Fu, B. Yang, J. Zeng, P. Chen, K. Liang, B. Kong, *Mater. Today Energy* **2021**, *21*, 100712, https://doi.org/10.1016/j.mtener.2021.100712.

[24] K. Fu, Z. Liu, Y. Yao, Z. Wang, B. Zhao, W. Luo, J. Dai, S. D. Lacey, L. Zhou, F. Shen, M. Kim, L. Swafford, L. Sengupta, L. Hu, *Nano Lett.* **2015**, *15*, 4664, https://doi.org/10.1021/acs.nanolett.5b01451.

[25] Y. Chen, R. Jamshidi, K. White, S. Çınar, E. Gallegos, N. Hashemi, R. Montazami, *J. Polym. Sci. Part B Polym. Phys.* **2016**, *54*, 2021, https://doi.org/10.1002/polb.24113.

[26] S. Stauss, I. Honma, *Bull. Chem. Soc. Jpn.* **2018**, *91*, 492, https://doi.org/10.1246/bcsj.20170325.

[27] A. Ojanguren, N. Mittal, E. Lizundia, M. Niederberger, *ACS Appl. Mater. Interfaces* **2021**, *13*, 21250, https://doi.org/10.1021/acsami.1c02135.

[28] X. Casas, M. Niederberger, E. Lizundia, *ACS Appl. Mater. Interfaces* **2020**, *12*, 29264, https://doi.org/10.1021/acsami.0c05262.

[29] X. Huang, D. Wang, Z. Yuan, W. Xie, Y. Wu, R. Li, Y. Zhao, D. Luo, L. Cen, B. Chen, H. Wu, H. Xu, X. Sheng, M. Zhang, L. Zhao, L. Yin, *Small* **2018**, *14*, 1, https://doi.org/10.1002/smll.201800994.

[30] M. H. Lee, J. Lee, S. K. Jung, D. Kang, M. S. Park, G. D. Cha, K. W. Cho, J. H. Song, S. Moon, Y. S. Yun, S. L. Kim, Y. W. Lim, D. H. Kim, K. Kang, *Adv. Mater.* **2021**, *33*, 2004902, https://doi.org/10.1002/adma.202004902.

[31] T. Mei, C. Wang, M. Liao, J. Li, L. Wang, C. Tang, X. Sun, B. Wang, H. Peng, *J. Mater. Chem. A* **2021**, *9*, 10104, https://doi.org/10.1039/d1ta01507a.

[32] Z. Wang, X. Li, Z. Yang, H. Guo, Y. J. Tan, G. J. Susanto, W. Cheng, W. Yang, B. C. K. Tee, *EcoMat* **2021**, *3*, 1, https://doi.org/10.1002/eom2.12073.

[33] P. Nadeau, D. El-Damak, D. Glettig, Y. L. Kong, S. Mo, C. Cleveland, L. Booth, N. Roxhed, R. Langer, A. P. Chandrakasan, G. Traverso, *Nat. Biomed. Eng.* **2017**, *1*, 1, https://doi.org/10.1038/s41551-016-0022.