Powering Electronic Devices from Salt Gradients in AA-Battery-Sized Stacks of Hydrogel-Infused Paper

Anirvan Guha, Trevor J. Kalkus, Thomas B. H. Schroeder, Oliver G. Willis, Chris Rader, Alessandro Ianiro, and Michael Mayer*

Strongly electric fish use gradients of ions within their bodies to generate stunning external electrical discharges; the most powerful of these organisms, the Atlantic torpedo ray, can produce pulses of over 1 kW from its electric organs. Despite extensive study of this phenomenon in nature, the development of artificial power generation schemes based on ion gradients for portable, wearable, or implantable human use has remained out of reach. Previously, an artificial electric organ inspired by the electric eel demonstrated that electricity generated from ion gradients within stacked hydrogels can exceed 100 V. The current of this power source, however, was too low to power standard electronics. Here, an artificial electric organ inspired by the unique morphologies of torpedo rays for maximal current output is introduced. This power source uses a hybrid material of hydrogel-infused paper to create, organize, and reconfigure stacks of thin, arbitrarily large gel films in series and in parallel. The resulting increase in electrical power by almost two orders of magnitude compared to the original eel-inspired design makes it possible to power electronic devices and establishes that biology’s mechanism of generating significant electrical power can now be realized from benign and soft materials in a portable size.

1. Introduction

The ability of strongly electric fish to produce external electrical discharges has inspired the design of artificial power sources since Alessandro Volta’s conception of the first battery.[1,2] Researchers have gravitated toward studying members of the Electrophorus genus, commonly known as electric eels, due to their exquisite physiological capacity for generating large voltages. For instance, the recently discovered Electrophorus voltai can produce 860 V from the aggregate of thousands of electrically active “electrocyte” cells stacked in series within its electric organ.[3,4] Inspired by the large voltages of electric eels, we recently engineered a soft, flexible, and potentially biocompatible power source from gradients of ions stored within hydrogels.[5] This system mimicked the organization of the eel’s electric organ by stacking a repeat sequence of high-salinity, cation-selective, low-salinity, and anion-selective hydrogels in series to produce over 100 V. The maximum power density of 27 mW m⁻² per repeat unit of this system was, however, too low to power electronic devices. Reaching practically useful power output from an artificial electric organ with the approximate size of a standard double-A (AA) battery would require a strategy for rapidly fabricating and stacking thin, large-area hydrogel films without curling, tearing, or wrinkling to ensure maximal electrical conduction between adjacent gels.[5]

Here, we took inspiration from the morphological adaptation of torpedo rays to overcome the limitations of the eel-inspired design and to introduce the ability to power small electronics. Specifically, in order to maximize current instead of voltage, we developed a practical method for rapidly stacking extremely thin sheets (<500 μm) with tunable surface area to assemble electrically active repeating units that are reminiscent of the stacks of electrocytes in the electric organs of torpedo rays (Figure 1). To this end, we introduce a hybrid material consisting of a thin porous scaffold infused with a hydrogel. The resulting next-generation artificial electric organ offers four enabling advancements over its predecessor: [5] First, it makes it possible to fabricate, manipulate, and stack thin, arbitrarily large hydrogel films in a practical and rapid fashion. Second, it introduces a modular strategy for bringing repeat sequences of these thin gel sheets into near-synchronous contact, thereby enabling reconfigurable serial or parallel arrangements of gel stacks with the ideal number of repeat units and surface area. Third, it provides a straightforward, mechanically supported platform to optimize hydrogel compositions as well as other system parameters. And fourth, it enables planar as well as rolled assembly strategies; rolling is particularly attractive because it is industrially used for paper and thin films, extremely rapid, and automatable.
2. Constructing an Artificial Electric Organ from Hydrogel-Paper Sheets

Both the artificial electric organ and its natural source of inspiration rely on selective movement of ions through aqueous solutions of electrolytes to generate voltage and current (Figure 1).\(^5,6\) Consequently, a significant portion of the electrical resistance of power generation schemes from ion gradients arises from the resistance of these electrolyte solutions to ion flux, which is directly proportional to the length of the conductive pathway and inversely proportional to its cross-sectional area.\(^7,8\) From this perspective, torpedo rays stand out as examples of electric fish that evolved to generate electric shocks of maximal power. Torpedo electrocytes are thin, polygonal sheets (Figure 1a), representing the ideal geometry for minimal internal resistance by maximizing cross-sectional area and limiting transport distance. Notably, Volta modeled the thin metal discs of his galvanic battery after the shape of torpedo electrocytes rather than those of electric eels, which are ribbon-shaped.\(^9\) For instance, the Atlantic torpedo Tetronarce nobiliana organizes up to 2000 columns of electrocytes in parallel to generate electrical discharges of over 1 kW, a tenfold higher power output than that of the electric eel.\(^6,10\)

Remarkably, the torpedo achieves this elevated power output even though both its individual electrocytes and electric organ as a whole produce significantly lower voltages than those of the eel\(^[11-13]\) ([Table 1]). This performance illustrates the importance of the torpedo’s flattened body shape with large area to accommodate a massively parallel arrangement of transverse columns of extremely thin electrically active cells to enable maximum current output.

To mimic the torpedo’s “stack of thin sheets” architecture, we created hierarchical double networks composed of sheets of paper infused with hydrogels of desired composition and function.\(^[14,15]\) Paper provides the material with mechanical support; we chose it as a scaffold because it is thin, porous, robust, hydrophilic, bendable, foldable, biodegradable, nontoxic, and potentially biocompatible. These qualities contribute to the increasing use of paper in a wide range of applications, including fluidics, robotics, and electrochemical devices and assays.\(^[16-18]\) To create paper-gel films, we dispensed precursor solutions of each hydrogel composition onto pieces of cellulose paper. The porosity and water-absorbent characteristics of the paper resulted in an autonomous, self-induced wicking action that infused the scaffold rapidly and evenly with hydrogel precursor solutions resulting in thin, coated sheets. Curing by UV-induced polymerization formed gel films attached firmly to the embedded substrate, creating paper-gel hybrid materials similar to those pioneered by the Whitesides’ group.\(^[19]\) Such paper-gels improve the mechanical stability compared to unsupported hydrogels, thereby limiting the risk of curling or wrinkling while retaining enough flexibility for bending, rolling, or folding during assembly (Section S2, Supporting Information).

Figure 1. Anatomy of the electric organ of the ray Tetronarce nobiliana and design of a paper-gel electric organ. a) T. nobiliana has a flat, disc-shaped body up to 1 m in diameter. A pair of electric organs are located on either side of the ray’s body. Each organ is a parallel arrangement of transverse columns consisting of hundreds to thousands of electrocytes in series (inset, left). The organization of these thin, large-area cells is reminiscent of stacks of thin sheets. The electrocytes here are drawn out of scale for clarity; the small thickness of the cells and small spacing between adjacent cells would make them impossible to distinguish from each other if they were drawn to scale. When activated by the ray’s nervous system, each electrocyte generates a transcellular potential of ≈60 mV from the asymmetrical flux of sodium and potassium through ion-selective channel proteins in its cell membranes (inset, right). b) Principle of the paper-gel electric organ. Sheets of paper, infused with hydrogel, are stacked in a repeating tetrameric sequence to generate additive potentials (inset, right). The red hydrogel is polymerized from uncharged monomers and stores a concentrated salt solution. The green hydrogel contains uncharged monomers and dilute salt. The yellow hydrogel contains positively charged monomers and is selective for permeation of anions. A scanning electron microscopy (SEM) image (inset, left) shows the cross section of a single paper gel. SEM images can be viewed in greater detail in Section S1, Supporting Information. c) Stacking these tetrameric gel cells in series and in parallel maximally scales voltage and current, respectively.

The blue hydrogel contains uncharged monomers and is selective for permeation of cations. The blue hydrogel contains uncharged monomers and dilute salt solution. The yellow hydrogel contains positively charged monomers and is selective for permeation of anions. A scanning electron microscopy (SEM) image (inset, left) shows the cross section of a single paper gel. SEM images can be viewed in greater detail in Section S1, Supporting Information. c) Stacking these tetrameric gel cells in series and in parallel maximally scales voltage and current, respectively.
and these benefits are associated with no apparent losses in ion selectivity or conductivity. To assemble a functioning artificial electric organ, we layered or rolled high-salinity, cation-selective, low-salinity, and anion-selective paper-hydrogel films in the same fashion as one would stack or roll four sheets of paper. Compared to the previous best design of the artificial electric organ,[5] this new design with 500 µm-thick gel films that made close electrical contact over the entire surface of the films improved the power density by one order of magnitude (Figure 2).

### 3. Tuning Hydrogel Compositions to Optimize Power Output

To increase the power further, we performed a rigorous optimization of the choice of charge-selective hydrogel, type of salt, concentration of salt, magnitude of salt gradient, and thickness of paper-gels. These studies revealed that sodium chloride, the principal salt of the first artificial electric organ,[5] produced relatively low voltage and power compared to other chloride salts. We identified lithium chloride (LiCl) as the best replacement for sodium chloride, because constraints in membrane fabrication and robustness make scaling to large cross-sectional areas currently impossible.[24–26] In contrast, the paper-gel electric organ provides a finger-sized (Figure 3; Figure S7, Supporting Information), potentially biocompatible and mechanically soft platform that can generate one million-fold larger currents in the range of milliamperes (Figure 2e) from benign components that include water, salt, hydrogel, and paper.

### 4. Powering Electronic Devices

Figure 3 demonstrates that these improvements in power density make it possible to reach an essential milestone toward portable, wearable, and implantable electrical power sources; they...
render artificial electric organs driven solely by ion gradients capable of powering real-world electronic devices. Moreover, they provide this power in a format of only 1.5 cm × 1.5 cm × 3.2 cm, corresponding to a volume of less than 8 mL, which is sufficiently small to envision future implantation. We used such a stack of 16 repeating units in series to power a circuit with a pre-programmed microcontroller chip that illuminated several light-emitting diodes (LEDs) in sequence (Figure S5, Supporting Information). This result, together with Video S1 and Section S8, Supporting Information, unequivocally establish that a relatively small stack of scaffolded hydrogels can power sequences of logical operations within a computer. Figure 3 also illustrates that straightforward reconfiguration of the dimensions of a paper-gel stack makes it possible to meet a range of operational demands for various electronic devices with low power consumption. For instance, while eight gel cells connected in series (volume = 3.6 mL) were able to illuminate a red LED, doubling the number of cells in series or in parallel doubled the open circuit voltage or the cross-sectional area of the stack and made it possible to illuminate three LEDs of different colors, powered solely by the paper-gel system. Modularity like this is beneficial for cases where either a threshold current or, as in the case of a green LED, a threshold voltage must be reached to operate various devices.

This modularity was made possible by a straightforward assembly and reconfiguration strategy as illustrated in Figure 4. Specifically, we took advantage of rapid and controlled tearing, bending, and folding along perforations to create and stack a desired number of layers of large-area tetrameric gel cells (Figure 4a). Figure 4b demonstrates that, even after infusing the paper scaffold with hydrogel and curing, the laser-cut subdivisions facilitate rapid tearing of tetrameric gel layers followed by restacking individual paper-gel cells to many cells in series or in parallel. In order to explore if paper-gel systems could potentially be assembled using a well-established industrial process, we took advantage of the mechanical flexibility of the paper-gel layers and rolled a long strip of the four different paper-gels layered on top of each other (Figure 4c). This process rapidly created repeating tetrameric sequences with each revolution. Figure 4c shows that cutting one such roll perpendicular to the direction of the rolling motion removed the lateral connection between the sheets and created a stack of three large-area gel cells in series. Industrial rolling machines can wind over one kilometer of paper per minute[27] applying this process to...
four-layered paper-gels with a width of 2 m could, within seconds, create a stack of 360 gel cells to generate at least 1 kW power. While the power of such stacks would dissipate rapidly upon contact between the gel sheets, we have demonstrated previously that applying a current through a discharged assembly of gels recharges these devices to recover and even exceed their original maximum power.\[5\]

5. Divergent Evolutionary Development of Natural Electric Organs

The innovations required to transform the artificial electric organ from a high-impedance scheme\[^5\] to a suitable power source for electronic devices recall the distinct evolutionary paths that resulted in electric eels and torpedoes. Achieving maximum power transfer requires matching the internal impedance of a power source with its load impedance.\[^28\] Since the 19th century, researchers have postulated that this principle explains the evolution toward the long and relatively narrow shape of the electric organs found in electric eels such that their internal resistance matches the low-conductivity environment of fresh water. Conversely, the strong electric organs found in fish native to high-conductivity salt water evolved in flat, wide rays that provided the development of organs with a low internal resistance.\[^29\] Contemporary portable electronic devices frequently have operating voltages of less than ten volts and are powered by batteries with sub-ohm output impedances.\[^30\] As powering such devices more closely approximates the evolutionary imperative of the torpedo than that of the eel, we found that reaching the power output necessary for doing useful electrical work required redesigning the artificial electric organ from the eel-inspired, long arrangement of electrically active cells in series for high voltage generation to the torpedo-inspired, flat, wide, and parallel arrangement for high current generation.

6. Single-Use Power Source for Low-Resource Environments

One remaining barrier to this system’s utility as a practical power source is, however, its inability to maintain maximal power output for extended periods of time. Once a tetrameric sequence of gels comes into contact, the salt gradient responsible for generating the potential begins to dissipate. The rate of this dissipation increases when the organ is connected to a load to do electrical work. For instance, an LED powered by a stack of paper-gel cells lost 90% of its maximum brightness within 5 min (Section S10, Figure S8, Supporting Information). Power-on-demand devices for single-use electronics, such as paper-based diagnostics,\[^18\,31\] may, however, constitute applications that are not affected by this limitation. These kinds of disposable point-of-care devices are often required in low-resource areas where traditional batteries are prohibitively expensive and their disposal may endanger the environment.\[^32\] The amount of power required for these devices, as well as for certain electrochemical or fluorescent diagnostic assays, is well within the reach of the paper-gel electric organ.\[^33\,34\]

For the successful application of paper-gel cells in such low-cost, non-toxic, and single-use electrical devices, it would be
critical that they can be dehydrated, stored without dissipation of the gradient, and activated on demand. To explore this possibility, we dehydrated individual paper-gel films, stored them for one day and then rehydrated the films before stacking them to form an electrically active gel cell. While the initial output power of this rehydrated artificial electric organ was only about half that of a freshly prepared one, its power output remained almost constant over 5 min. By this time, the ionic gradient of the freshly prepared artificial organ had partially dissipated, resulting in approximately half of its initial power and hence both versions provided comparable power output (Section S11, Figure S9, Supporting Information). Considering that all components of these paper-gel electric organs are environmentally friendly and potentially biodegradable, these results hint at the artificial organ’s promise as a safely disposable power source that delivers electricity on demand by harvesting water from the environment, or by a process as simple as adding readily available aqueous solutions.

7. Conclusions

Strongly electric fish show that the energy stored within ionic gradients can generate powerful and useful discharges...
of electricity within the constraints of living organisms. The work presented here establishes a straightforward and robust method of powering electronic devices from rapidly assembled stacks of ionic gradients. Since the total volume of these potentially biocompatible hydrogel stacks is smaller than 10 mL and would readily fit into a body cavity, and since the peak power density of this paper-gel electric organ represents roughly 1/10th of the power density of the most powerful electric fishes, we suggest that the vision of implantable artificial electric organs has made one more encouraging step toward realization. Moreover, with further improvements, artificial electric organs have the potential to reach and possibly exceed the performance of biological electric organs. These improvements may include the use of thinner scaffolds and gel films, further optimized hydrogel compositions and polymerization conditions, or laminating the high and low-salt compartment gels with ultra-thin films. Molecular layers or 2D materials that are capable of charge- or metabolism, then the application of the paper-gel electric gradients that are physiologically maintained in humans such as to maintain or regenerate ion gradients, perhaps by exploiting even ion-selective permeation. Even without these improvements, however, the work presented here establishes that artificial electric organs from stacks of paper-gels can do useful electric work, a feat that was out of reach of the first artificial electric organ presented recently. If future designs can maintain or regenerate ion gradients, perhaps by exploiting gradients that are physiologically maintained in humans such as the proton concentration in the stomach versus fluids in the surrounding tissue (Section S12, Supporting Information) or by generating ions in situ from products of human metabolism, then the application of the paper-gel electric organ may expand to powering portable, wearable, and possibly even implantable electronics.

8. Experimental Methods

Materials and Equipment: All chemicals were purchased from Sigma Aldrich (Merck-KGaA) except for 40% w/v 37.5:1 acrylamide/N,N'-methylenebisacrylamide (henceforth “bis”) solution (Bio-Rad). Water was purified to 18.2 MΩ cm with a PURELAB Flex II purifier (ELGA LabWater, Veolia). Either grade 1 chromatography paper (thickness = 0.17 mm) (Whatman plc) or MC-5 lens-cleaning tissue (thickness = 0.04 mm) (Thorlabs Inc.) were used as paper substrates. These paper substrates were perforated using a Speedy 300 laser cutter (Trotec) or a Cricut Maker cutting machine (Cricut Inc.) equipped with a perforation blade. All gels were cured with a Mineralight UV Display lamp (UVP, Analytik Jenna) containing two 25-W, 302-nm UV tubes (Ushio Inc.).

Graphite felt was made of 100% hexacyanoferrate(II), 100% potassium hexacyanoferrate(III), and 1 m KCl per 1 cm² of felt in the area that would come into contact with the terminal gels; this solution participated in the oxidation-reduction reaction that converted the charges carried by ions within the gels to electrons within the rest of the circuit. These prepared graphite felt electrodes were placed in contact with either end of a stack of paper-gels and a small, consistent amount of pressure was applied to ensure even and continuous contact. Voltages were recorded with a Tektronix DMM4040 digital multimeter set to high input impedance mode. To calculate maximum power density, a resistor was connected in series with a gel stack and the voltage across the resistor was measured (see Section S13, Supporting Information).

Optimization of Paper-Gel System: For each trial an individual paper-gel cell was prepared; that is, one sequence of high-salinity, cation-selective, low-salinity, anion-selective, and high-salinity paper-gels. The substrate of each gel was a 1.5 cm × 1.5 cm square of paper. Chromatography paper was used for all tests except where noted. A wooden clothespin was used to hold the electrodes in contact with the paper-gel stack, and the open-circuit voltage and maximum power density of each stack were measured. The composition of the gels used in each experiment was as follows, organized by panel from Figure 2:

- a) High-salinity gel: 1.5 m NaCl; cation-selective gel: 2 m SPAR or 2 m AMPS; low-salinity gel: 0.015 m NaCl; anion-selective gel: 2 m APTAC.
- b) High-salinity gel: 1.5 m HCl, 1.5 m LiCl, 1.5 m NaCl, 1.5 m KCl, 1.5 m CsCl, or 1.5 m CaCl₂; cation-selective gel: 2 m AMPS; low-salinity gel: 0.015 m HCl, 0.015 m LiCl, 0.015 m NaCl, 0.015 m KCl, 0.015 m CsCl, or 0.015 m CaCl₂; anion-selective gel: 2 m APTAC.
- c) High-salinity gel: 1.5 m LiCl, 3 m LiCl, or 6 m LiCl; cation-selective gel: 2 m AMPS; low-salinity gel: 0.015 m LiCl, 0.03 m LiCl, or 0.06 m LiCl; anion-selective gel: 2 m APTAC.
- d) High-salinity gel: 6 m LiCl; cation-selective gel: 2 m AMPS; low-salinity gel: 0.006 m LiCl, 0.06 m LiCl, or 0.6 m LiCl; anion-selective gel: 2 m APTAC.
- e) High-salinity gel: 6 m LiCl; cation-selective gel: 2 m AMPS; low-salinity gel: 0.06 m LiCl; anion-selective gel: 2 m APTAC.

Tearing and Restacking Method of Assembling Paper-Gel Cells in Series: To stack many paper-gel cells rapidly in series, hydrogel precursor solution was dispensed onto large pieces of chromatography paper, with perforations subdividing the sheet into the requisite 1.5 cm × 1.5 cm squares. For example, to create a stack of four paper-gel cells with dimensions of 1.5 × 1.5 cm per paper-gel, a 3 × 3 cm piece of paper would be prepared for each gel type, with perforations dividing the papers into four 1.5 × 1.5 cm squares. After curing, these large-area paper-gels were stacked into one sequence of high-salinity gel, cation-selective gel, low-salinity gel, and anion-selective gel before tearing along the perforations to create two stacks of equal size. Then these two halves would be stacked in series and torn again, repeating the process to achieve rapidly the desired number of cells in series.

Powering LEDs with Paper-Gel Stacks: To power LEDs, the tearing and restacking method was used to create at least eight paper-gel
cells in series. The substrate of each paper-gel was a 1.5 cm × 1.5 cm square of chromatography paper. The resulting open-circuit voltage was measured as described previously, and then the stack was connected in series with red (Sloan LS-R91H), yellow (RND 135-00030), and green (RND 135-00177) LEDs, one at a time. A force-sensitive resistor (FS402, Interlink) was used to maintain a constant pressure of ~6.5 kPa on each paper-gel stack during all measurements and pictures.

Creating Large-Area Repeating Tetrameric Paper-Gel Sequences by Rolling:

To create a rapidly and potentially automatizable procedure for the fabrication of paper-gel cells with large contact area, a rectangle of chromatography paper with a width of 6 cm was cut for each hydrogel type. The lengths of each rectangle were as follows: high-salinity gel, 13.8 cm; cation-selective gel, 14.5 cm; low-salinity gel, 15.1 cm; anion-selective gel, 15.7 cm. After fabricating each paper-gel as previously described, the rectangles were stacked such that one of the short edges of each rectangle was in perfect alignment, and the opposite ends of the rectangles were offset from each other to account for the difference in circumferential path length for the different gels. The offset end was pressed onto the surface of a 0.8 cm diameter rod and the gels were rolled around the rod. Once the gels had been rolled fully, they were pulled off the rod and a cut was made along the leading edge of the layered paper-gels down to the center of the roll to create three independent tetrameric gel cells.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements

The authors thank Jerry Yang for discussions, critical comments on the manuscript and suggestions. The authors are grateful to U. Steiner’s group for the use of their Formlabs 3D Printer. Laser cutting was performed at Fablab Fribourg. Research reported in this publication was supported by the National Centres of Competence in Research (NCCR) from the Swiss National Science Foundation (SNSF) on Bioinspired Materials and by a PIRE grant on Bio-Inspired Materials and Systems funded jointly by the National Science Foundation of the US (NSF) and the SNSF. T.B.H.S. was funded by a SNSF Postdoc Mobility fellowship. The authors are also thankful to the Adolphe Merkle Foundation for support. [Correction added on 19 May 2022, after first online publication: CSAL funding statement has been added.]

Open Access Funding provided by Universite de Fribourg.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

A.G. and M.M. conceived the project. A.G., T.J.K., and M.M. designed the experiments. A.G., T.J.K., C.R., A.I., and O.G.W. collected all data. T.B.H.S. provided analysis on the impact of salt choice on the power output of the artificial electric organ and linked the innovations presented here to the divergent evolutionary paths of electric eels and torpedoes. A.G., T.B.H.S., and M.M. wrote the manuscript.

Data Availability Statement

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

Keywords

bioinspired materials, energy storage, hydrogels, paper

Received: March 4, 2021
Revised: May 17, 2021
Published online: June 24, 2021

[1] A. Volta, Philos. Trans. R. Soc. 1800, 90, 403.
[2] M. Piccolino, Trends Neurosci. 2000, 23, 147.
[3] C. D. de Santana, W. G. Crampton, C. B. Dillman, R. G. Frederico, M. H. Sabaj, R. Covain, J. Ready, J. Zuanon, R. R. de Oliveira, R. N. Mendes-Júnior, Nat. Commun. 2019, 10, 4000.
[4] A. L. Gotter, M. A. Kaetzl, J. R. Dedman, Comp. Biochem. Physiol., Part A: Mol. Integr. Physiol. 1998, 119, 225.
[5] T. B. H. Schroeder, A. Cuha, A. Lamoureux, G. VanRenterghem, D. Sept, M. Shtein, J. Yang, M. Mayer, Nature 2017, 552, 214.
[6] M. V. Bennett, in Fish Physiology, Elsevier, Amsterdam, The Netherlands 1971, pp. 347–491.
[7] R. Lacey, Ocean Eng. 1980, 7, 1.
[8] P. Długołęcki, A. Gambier, K. Nijmeijer, M. Wessling, Environ. Sci. Technol. 2009, 43, 6888.
[9] A. K. Sethi, The European Edisons: Volta, Tesla, and Tigerstedt, Springer, Berlin, Germany 2016.
[10] M. V. L. Bennett, M. Wurzel, H. Grundfest, J. Gen. Physiol. 1971, 44, 757.
[11] K. C. Catania, Proc. Natl. Acad. Sci. USA 2016, 113, 6979.
[12] D. Nachmansohn, R. T. Cox, C. W. Coates, A. L. Machado, J. Neurophysiol. 1942, 5, 499.
[13] R. T. Cox, C. W. Coates, M. V. Brown, Ann. N. Y. Acad. Sci. 1946, 47, 487.
[14] J. P. Gong, Y. Katsuyama, T. Kurokawa, Y. Osada, Adv. Mater. 2003, 15, 1155.
[15] J.-Y. Sun, X. Zhao, W. R. Illeperuma, O. Chaudhuri, K. H. Oh, D. J. Mooney, J. J. Vlassak, S. Zuo, Nature 2012, 489, 133.
[16] X. Li, D. R. Ballerini, W. Shen, Biomicrofluidics 2012, 6, 011301.
[17] R. V. Martinez, C. R. Fish, X. Chen, G. M. Whitesides, Adv. Funct. Mater. 2012, 22, 1376.
[18] J. Hu, S. Wang, L. Wang, F. Li, B. Pingguan-Murphy, T. J. Lu, F. Xu, Biosens. Bioelectron. 2014, 54, 585.
[19] R. Derda, A. Laromaine, A. Mammoto, S. K. Y. Tang, T. Mammoto, D. E. Ingber, G. M. Whitesides, Proc. Natl. Acad. Sci. USA 2009, 106, 18457.
[20] P. Długołęcki, B. Anet, S. J. Metz, K. Nijmeijer, M. Wessling, J. Membr. Sci. 2010, 346, 163.
[21] A. H. Galama, D. A. Vermaas, J. Veerman, M. Saakes, H. H. M. Rijnaarts, J. W. Post, K. Nijmeijer, J. Membr. Sci. 2014, 467, 279.
[22] Y. Mei, C. Y. Tang, Desalination 2018, 425, 156.
[23] H.-K. Kim, M.-S. Lee, S.-Y. Lee, Y.-W. Lee, N.-J. Jeong, C.-S. Kim, J. Mater. Chem. A 2015, 3, 16302.
[24] J. Feng, M. Graf, K. Liu, D. Ovchinnikov, D. Dumcenco, M. Heiranian, V. Nandigana, N. R. Aluru, A. Kis, A. Radenovic, Nature 2016, 536, 197.
[25] W. Guo, L. Cao, J. Xia, F.-Q. Nie, W. Ma, J. Xue, Y. Song, D. Zhu, Y. Wang, L. Jiang, Adv. Funct. Mater. 2010, 20, 1339.
[26] X. Liu, M. He, D. Calvani, H. Qi, K. B. S. S. Gupta, H. J. M. de Groot, G. J. A. Sevink, F. Buda, U. Kaiser, G. F. Schneider, Nat. Nanotechnol. 2020, 15, 307.
[27] F. A. Guy, S. J. Chambliss, J. K. Beckett, B. M. Baldwin, WO/2004/033350, 2004.
[28] S. N. Makarov, R. Ludwig, S. J. Bitar, Practical Electrical Engineering, Springer, Berlin, Germany 2016.
[29] D. Ferrier, Nature 1883, 28, 214.
[30] Product Technical Data Sheets, https://www.duracell.com/en-us/techlibrary/product-technical-data-sheets/ (accessed: May 2020).
[31] Y. Lin, D. Gritsenko, Q. Liu, X. Lu, J. Xu, ACS Appl. Mater. Interfaces 2016, 8, 20501.
[32] S. Choi, Biotechnol. Adv. 2016, 34, 321.
[33] H. Liu, R. M. Crooks, Anal. Chem. 2012, 84, 2528.
[34] N. K. Thom, K. Yeung, M. B. Pillion, S. T. Phillips, Lab Chip 2012, 12, 1768.
[35] H. Tan, K. G. Marra, Materials 2010, 3, 1746.
[36] T. H. Nguyen, A. Fraiwan, S. Choi, Biosens. Bioelectron. 2014, 54, 640.
[37] X. Liu, H. Gao, J. E. Ward, X. Liu, B. Yin, T. Fu, J. Chen, D. R. Lovley, J. Yao, Nature 2020, 578, 550.
[38] A. Mateescu, Y. Wang, J. Dostalek, U. Jonas, Membranes 2012, 2, 40.
[39] J. Torgersen, X.-H. Qin, Z. Li, A. Ovsianikov, R. Liska, J. Stampfl, Adv. Funct. Mater. 2013, 23, 4542.
[40] G. Villar, A. D. Graham, H. Bayley, Science 2013, 340, 48.
[41] K. T. Sapra, H. Bayley, Sci. Rep. 2012, 2, 848.
[42] K. Ogawa, E. Kokufuta, Langmuir 2002, 18, 5661.
[43] J. Veerman, M. Saakes, S. J. Metz, G. J. Harmsen, J. Appl. Electrochem. 2010, 40, 1461.