This work demonstrates a new method to stabilize the interface between a volume-controlling scaffold and lithium metal through the simple and fast electroplating of silver. The electroplating platform motivates future studies of new metal and metal alloys that can be readily electroplated onto scaffolds to stabilize these cells. While promising, lithium metal batteries are still far from commercial targets for performance and safety and, unfortunately, as we know from the age-old proverb of scientific progress: breakthroughs can't be scheduled. However, with developments such as these and the overall rapid and continued progress of this field, it is increasingly likely that we will see lithium metal anodes used in batteries.

1. Mizushima, K., Jones, P.C., Wiseman, P.J., and Goodenough, J.B. (1980). LixCoO2 (0<x<-1): A new cathode material for batteries of high energy density. Mater. Res. Bull. *15*, 783–789.

2. Yoshino, A., Sanechika, K., Nakajima, T. (1985). Secondary Battery. US4668595A.

3. Tu, Z., Choudhury, S., Zachman, M.J., Wei, S., Zhang, K., Kourkoutis, L.F., and Archer, L.A. (2017). Designing artificial solid-electrolyte interphases for single-ion and high-efficiency transport in batteries. Joule *1*, 394–406.

4. Kim, J.Y., Kim, A.-Y., Liu, G., Woo, J.-Y., Kim, H., and Lee, J.K. (2018). Li_4SiO_4-Based artificial passivation thin film for improving interfacial stability of Li metal anodes. ACS Appl. Mater. Interfaces *10*, 8692–8701.

5. Liang, Z., Lin, D., Zhao, J., Lu, Z., Liu, Y., Liu, C., Lu, Y., Wang, H., Yan, K., Tao, X., and Cui, Y. (2016). Composite lithium metal anode by melt infusion of lithium into a 3D conducting scaffold with lithiophilic coating. Proc. Natl. Acad. Sci. USA *113*, 2862–2867.

6. Liu, L., Yin, Y.-X., Li, J.-Y., Li, N.-W., Zeng, X.-X., Ye, H., Guo, Y.-G., and Wan, L.-J. (2017). Free-standing hollow carbon fibers as high-capacity containers for stable Lithium metal anodes. Joule *1*, 563–575.

7. Zhang, R., Chen, X., Shen, X., Zhang, X.-Q., Chen, X.-R., Cheng, X.-B., et al. (2018). Coralloid carbon fiber-based composite Lithium anode for robust lithium metal batteries. Joule *2*, this issue, 764–777.

8. Lin, D., Liu, Y., Liang, Z., Lee, H.-W., Sun, J., Wang, H., Yan, K., Xie, J., and Cui, Y. (2016). Layered reduced graphene oxide with nanoscale interlayer gaps as a stable host for lithium metal anodes. Nat. Nanotechnol. *11*, 626–632.

9. Luo, W., Gong, Y., Zhu, Y., Li, Y., Yao, Y., Zhang, Y., Fu, K.K., Pastel, G., Lin, C.F., Mo, Y., et al. (2017). Reducing interfacial resistance between garnet-structured solid-state electrolyte and Li-Metal anode by a Germanium layer. Adv. Mater. *29*, 1606042.

10. The Silver Institute (2017). World Silver Survey 2017. http://s22.q4cdn.com/579360173/files/doc_news/silver_updates/2017-World-Silver-Survey-2.pdf.

Preview

Maxing Out Water Desalination with MXenes

Rahul Malik[1,*]

In this issue of *Joule*, Guoxiu Wang, Yury Gogotsi, and collaborators design and synthesize highly porous MXene electrodes that are resistant to nanosheet restacking and deliver high electroadsorption capacity for capacitive deionization (CDI) of saline water. In CDI cells constructed with aerogel-like $Ti_3C_2T_x$ MXene electrodes, an adsorption capacity of 118 mg/cm^3 (45 mg/g) was achieved in a 10,000 mg/L salt solution, more than one order of magnitude greater than carbon-based electrode materials.

As increasing billions face the regular threat of water stress due to clean water demand overwhelming supply, we cannot question the scale and severity of this global crisis. Nevertheless, without specific examples it is difficult to capture the stark reality of the situation. This year Cape Town issued warnings to its near four million inhabitants of a fast-approaching "Day Zero" (in several days to months), when municipal water taps would need to be shut off and subsistence rationing instituted.[1] Similar acute shortages are also coming to a head in a growing number of major population centers, from Sao Paulo to Bengalaru.[2,3]

Undoubtedly, humanity must reexamine its stewardship of earth's water resources, but just like the incredible challenge of transitioning to a sustainable decarbonized energy system, workable solutions to the global water crisis must also navigate through complex relationships with political, economic, moral, and technological factors. In particular, when examining the technological solution space, it becomes very helpful to view water through the lens of energy (and vice versa), the so-called "Water-Energy Nexus."

To illustrate, industrial energy production consumes a significant fraction of fresh water supplies, and the principal problem in clean water production is separating salt from water in an energy-efficient way.[4] While widely deployed desalination technologies do exist, they come with high costs, and none operate close to the thermodynamic energy minimum for removing ions from solution.

[1]*Joule*, Cell Press, 50 Hampshire Street, 5th Floor, Cambridge, MA 02139, USA

*Correspondence: rmalik@cell.com

https://doi.org/10.1016/j.joule.2018.04.001

Capacitive deionization (CDI) is an exciting electrochemical approach that traditionally removes salt ions from water through electrosorption[5] and, unlike alternatives such as distillation and reverse osmosis, requires neither elevated temperature nor pressure to operate. Furthermore, only a low applied voltage (~1-1.4 V) and an electric charging current that scales with system size are required as input. The modular design thus avoids large capital expenditures such as high pressure pumps or heat sources.

Though more complex cell architectures have been investigated, in its simplest form a CDI cell consists of two porous electrodes, typically carbon based, separated by either an open feed flow channel or porous dielectric separator. At one end the feed water is introduced, and when a cell voltage is applied, the salt ions migrate to the electrodes' electric double layers and are held in place allowing fresh water to flow out. Then, in the discharge step, the ions are released into a brine stream. CDI systems perform most efficiently when the feed has lower salinity, however, and are therefore currently suited to treat brackish water rather than seawater. Only with significant efficiency improvements can the technology make its way into industrial-scale seawater desalination.

Though the principal concept of CDI technology was established as early as 1960, many exciting developments have unfolded within the last 10 years in this rejuvenated area of research,[5] and one promising direction draws inspiration from recent advances in energy storage electrode materials.[6] In this issue of *Joule*, Guoxiu Wang, Yury Gogotsi, and collaborators build on the concept. They design and synthesize highly porous MXene electrodes that are resistant to nanosheet restacking and deliver high electroadsorption capacity for capacitive deionization of saline water.[7] In CDI cells constructed with aerogel-like $Ti_3C_2T_x$ MXene electrodes, an adsorption capacity of 118 mg/cm^3 (45 mg/g) was achieved in a 10,000 mg/L salt solution, more than an order of magnitude greater than carbon-based electrode materials.

Discovered in 2011, MXenes are a class of 2D transition metal carbides, carbonitrides, and nitrides (where "M" is the transition metal and "X" is carbon and/or nitrogen) with remarkable materials properties important in applications ranging from biology and medicine, to electromagnetic interference shielding, and to, of course, energy storage.[8] Also, they can be derived through a straightforward synthesis procedure, simply by etching bulk layered structures known as MAX phases (a family of ternary carbides and nitrides) with hydrofluoric acid (HF), which leaves behind exfoliated nanosheets terminated with hydrophilic functional groups (such as OH, O, and F) that enhance capacitance.

To take advantage of the favorable properties of MXenes as electrode materials, an important consideration is to ensure that a large specific surface area is available and maintained to maximize salt electrosorption. Unfortunately, there is a driving force to restack the exfoliated sheets due to van der Waal's forces between layers, which leaves less surface exposed. Therefore, after treating Ti_3AlC_2 powders with HF, the authors perform an additional treatment in chloroform, which drives solvent molecules to intercalate into the MXene flakes, encouraging further delamination into thinner sheets. This is followed by a vacuum freeze-drying procedure that promotes pore formation and leaves behind a crumpled 3D porous matrix of exfoliated nanosheets.

Remarkably, the porous $Ti_3C_2T_x$ electrode exhibits a high specific capacitance of 410 F/cm^3 (~156 F/g), almost double that of restacked $Ti_3C_2T_x$ (synthesized without the additional treatments) and more than an order of magnitude greater than activated carbon. In CDI cells, the porous $Ti_3C_2T_x$ electrode's adsorption capacity is also 2.1 times higher than the restacked version and 12.8 times activated carbon. Furthermore, the porous electrode design enhances mass transport properties, reaching the maximum electroadsorption capacitance in a shorter time compared to restacked $Ti_3C_2T_x$, activated carbon, and electrodes composed of other materials.

Searching for further mechanistic insight into the origin of superior electrosorption and salt storage with their electrode design, the authors find that in addition to capacitive storage, high-rate ion intercalation is enhanced and contributes more than one tenth of salt adsorption. MXenes are well known to incorporate structural water into their layers in aqueous environment,[9] and the enhanced ion intercalation kinetics identified in this work are consistent with decreased charge-transfer activation energy at the surface (from partial solvation from water) and rapid "surface-like" diffusion within the interlayer spacing as observed in a number of 2D materials with nanoconfined fluids.[10]

Overall, this work is a shining example that new ideas and materials borrowed from other disciplines can breathe life into decades-old research. While MXenes have been investigated previously for CDI applications,[11] this work represents a significant step forward in performance through rational synthesis and electrode engineering guided by fundamental materials science. In the background of imminent water crisis, such advances in capacitive deionization are welcome and cannot come fast enough.

1. Lyster, R. Counting down to day zero in Cape Town. *The New Yorker*. March 1, 2018. https://www.newyorker.com/tech/elements/counting-down-to-day-zero-in-cape-town.

2. The 11 cities most likely to run out of drinking water - like Cape Town. *BBC*. February 11, 2018. http://www.bbc.com/news/world-42982959.

3. Subramanian, S. India's silicon valley is dying of thirst. Your city may be next. *Wired*. May 2, 2017. https://www.wired.com/2017/05/why-bangalores-water-crisis-is-everyones-crisis/.

4. Urban, J.J. (2017). Emerging scientific and engineering opportunities within the water-energy nexus. Joule *1*, 665–688.

5. Suss, M.E., Porada, S., Sun, X., Biesheuvel, P.M., Yoon, J., and Presser, V. (2015). Water desalination via capacitive deionization: what is it and what can we expect from it? Energy Environ. Sci. *8*, 2296–2319.

6. Suss, M.E., and Presser, V. (2018). Water desalination with energy storage electrode materials. Joule *2*, 10–15.

7. Bao, W., Tang, X., Guo, X., Choi, S., Wang, C., Gogotsi, Y., and Wang, G. (2018). Porous cryo-dried MXene for efficient capacitive deionization. Joule *2*, this issue, 778–787.

8. Anasori, B., Lukatskaya, M.R., and Gogotsi, Y. (2017). 2D metal carbides and nitrides (MXenes) for energy storage. Nature Reviews Materials *2*, 16098.

9. Okubo, M., Sugahara, A., Kajiyama, S., and Yamada, A. (2018). MXene as a Charge Storage Host. Acc. Chem. Res. *51*, 591–599.

10. Augustyn, V., and Gogotsi, Y. (2017). 2D materials with nanoconfined fluids for electrochemical energy storage. Joule *1*, 443–452.

11. Srimuk, P., Kaasik, F., Krüner, B., Tolosa, A., Fleischmann, S., Jäckel, N., Tekeli, M.C., Aslan, M., Suss, M.E., and Presser, V. (2016). MXene as a novel intercalation-type pseudocapacitive cathode and anode for capacitive deionization. J. Mater. Chem. A Mater. Energy Sustain. *4*, 18265–18271.