

The Waterloo Institute for Nanotechnology: Societal Impact and a Sustainable Future

The Waterloo Institute for Nanotechnology (WIN) is Canada's largest nanotechnology institute and a world leader in the broader areas of nanoscience and nanotechnology. Located at the University of Waterloo (UW) in Waterloo, Ontario, Canada, it is truly an interdisciplinary research enterprise representing nine departments and schools spanning across the Faculties of Engineering, Science, and Mathematics.

As WIN enters its 12th year of operation, we have set out to be world leaders in nanoscience and nanotechnology, meeting the targets for the United Nations Sustainable Development Goals (UN SDG) as set out in 2015 that will lead to sustainable development, economic growth, and environmental protection. We are pleased to assemble this [WIN Virtual Issue](#) for ACS Nano, highlighting our members' research breakthroughs as shared in ACS publications, with special attention to energy harvesting and storage technology.

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The University of Waterloo. The University of Waterloo (UW) in Waterloo, Canada was founded in 1957 to be an academic center for innovation and entrepreneurship to tackle some of the world's serious problems at the time. During the height of the Cold War and the Space Race, there was a critical need for more scientists and engineers in North America, and the founders envisioned a new type of education to train engineers and technicians through cooperative education. This bold and daring approach to the education system, which has made UW well-known throughout the world, enables academic and research excellence while serving the needs of society throughout its history to present day.

Over the past 60 years, UW has become one of the world leaders in engineering, mathematics, and science, with 2019 QS world subject rankings of #46 for Engineering & Technology, #43 for Mathematics, #22 for Computer and Information Sciences, and #84 for Materials Science. In addition, for the past two decades, UW has been continuously recognized as Canada's Most Innovative University by *Maclean's Magazine* and *The Globe and Mail University Report*, citing UW as the most innovative institution for higher learning, the best experiential learning, and generating graduates best prepared for careers.

This past year has also brought some momentous achievements: with the Nobel Prize in Physics awarded to Professor Donna Strickland in November 2018 for her work on chirped pulse laser amplification technology (only the third woman in history to receive this prestigious honor), and with the first images of a black hole by Professor Avery Broderick in April 2019.

The Waterloo Institute for Nanotechnology. Interdisciplinary research is a cornerstone of innovation—addressing today's complex challenges requires thinking beyond traditional disciplines to tackle large-scale challenges and to find practical solutions. The importance of nanotechnology as a truly interdisciplinary, enabling research area was recognized by UW early on in its development, and in 2008 the Waterloo Institute for Nanotechnology was founded. It is the largest nanotechnology institute in Canada and one of the premier institutes in the world. Thus, WIN is uniquely positioned to bridge the entire scale of the nanotechnology research landscape—from quantum phenomena to nanoscale materials, to micromachinery and sensors, to devices that we use every day.

The Waterloo Institute for Nanotechnology is housed in the Mike & Ophelia Lazaridis Quantum-Nano Centre (QNC), a 250,000 sq ft building with state-of-the-art infrastructure (Figure 1). The QNC facilities include the Molecular Beam Epitaxy Laboratory (HRXRD, RGA, pyrometry, and thermometry), the Metrology Suite (TEM, SEM-FIB, AFM, SAXS, and SQUID), and the QuantumNano Fab Facility (with e-beam lithography, ALD, CVD, spin coating, and ion milling capabilities). Other nanotechnology facilities at UW include the Giga-to-Nano Electronics (G2N) Centre, the Waterloo Advanced Technology Laboratory (WATLab), the Centre for Advanced Photovoltaic Devices & Systems (CAPDS), and the Centre for Integrated Radio Frequency Engineering (CIRFE).

In addition, WIN constantly strives to improve and to learn from the best, with strategic international relationships being a main focus at WIN. To date, WIN has partnered with 24 international universities and institutes in 14 countries.

Societal Impact and a Sustainable Future.



Since its inception in 2008, 97 researchers have joined WIN, boasting an impressive publication record and numerous invention disclosures, patent filings, and start-up companies. The Waterloo Institute for Nanotechnology strives to promote research excellence in four key theme areas of nanotechnology—*Smart and Functional Materials*, *Connected Devices*, *Next-Generation Energy Systems*, and *Therapeutics and Theranostics*—

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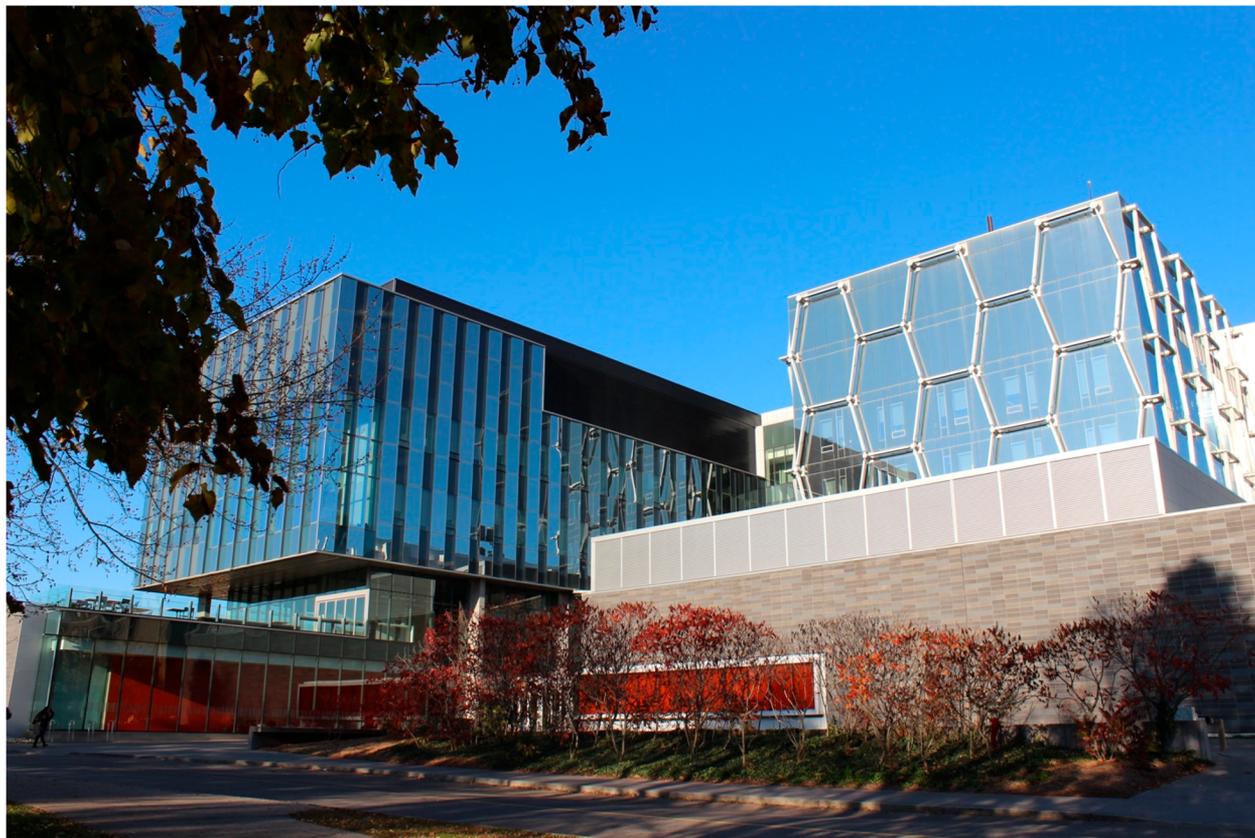


Figure 1. Mike & Ophelia Lazaridis Quantum Nano Centre at the University of Waterloo. Image credit: Isabella McKenzie.

creating both economic and societal impact and a sustainable future.

The Waterloo Institute for Nanotechnology is uniquely positioned to bridge the entire scale of the nanotechnology research landscape—from quantum phenomena to nanoscale materials, to micromachinery and sensors, to devices that we use every day.

To ensure this outcome, WIN has mapped its thematic areas with the United Nations Sustainable Development Goals (UNSDG), which were designed not only to help end poverty and other deprivations but also to adopt strategies to tackle global challenges such as improving health and living conditions, leading to sustainable development, economic growth, and environmental protection.

The Waterloo Institute for Nanotechnology is directly in tune with these global challenges, seeking solutions to ensure good health (SDG 3), clean water and energy (SDGs 6 and 7), industry and innovation (SDG 9), and climate action (SDG 13). Below are several examples of how WIN members' research maps with several UN SDGs. Figure 2 shows the UN SDGs mapped to the four WIN thematic research areas.

Members of WIN have an impressive record of publications in top scientific journals. Researchers at WIN have published approximately 200 articles in American Chemical Society journals, with 30 in *ACS Nano* since 2008 in the key theme areas of nanotechnology mentioned above. For the themes of

Smart and Functional Materials and *Connected Devices*, publication topics include surface modification and nanostructure formation,^{1–6} polymer studies,^{7,8} transparent conductive electrodes,⁹ and nanocellulose applications.¹⁰

In the theme area of *Therapeutics and Theranostics*, WIN members have published in *ACS Nano* on pharmaceutical sciences,¹¹ bacterial pathology,¹² biosensor development,¹³ DNA functionalization,^{14,15} tissue engineering,¹⁶ and cancer treatment.¹⁷

Energy-Storage Technologies. Among the most impactful publications from WIN are notably in clean and affordable energy. The Waterloo Institute for Nanotechnology is fortunate to be home to world-leading researchers in this field, as well as several rising stars working on discovering new solutions to this significant global challenge, especially in low-dimensional materials for supercapacitors,¹⁸ fuel cells,¹⁹ solar cell technology,^{20,21} water splitting,²² rechargeable zinc-ion battery technology,²³ and carbon nanotube technologies for energy storage.^{24,25}

Lithium-Chemistry-Based Battery Technology. The Waterloo Institute for Nanotechnology is proud to have two distinguished researchers in electrochemical energy storage technologies as members, Linda Nazar of the Department of Chemistry, and Zhongwei Chen of the Department of Chemical Engineering. They have both published extensively on the potential of lithium-ion, and post-lithium-ion battery technology and are considered world experts in the field.

In response to the world's demand for clean energy for household, industry, personal electronic devices, and transportation, *etc.*, battery technology is providing ways to store energy from intermittent sources (wind, solar) to use as needs arise. This technology is especially relevant for the advent of

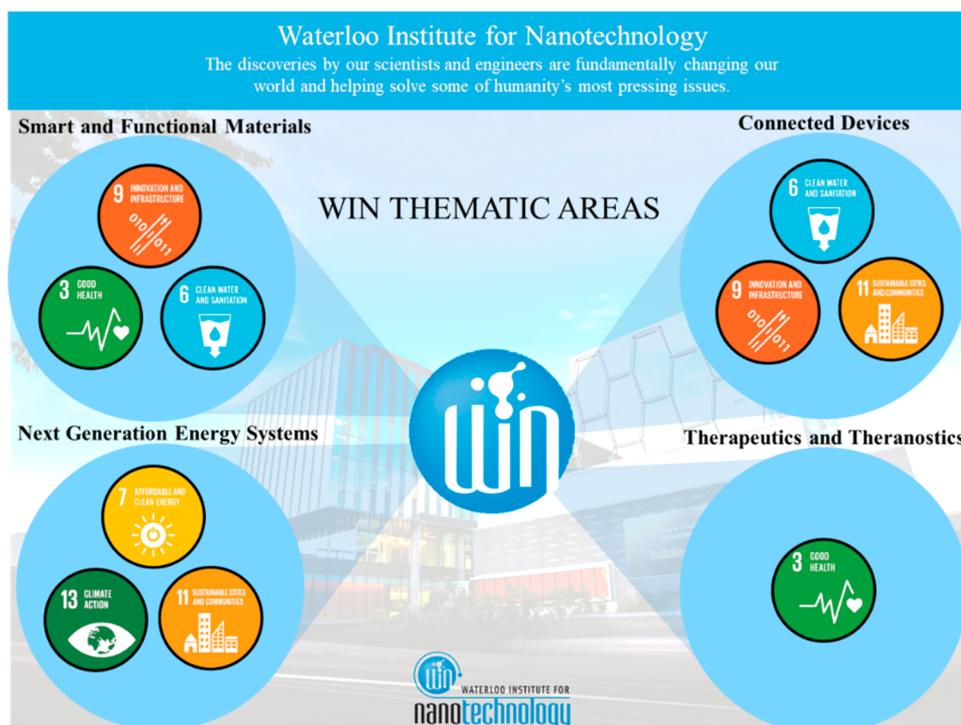


Figure 2. United Nations Sustainable Development Goals (UN SDG) mapped to the Waterloo Institute for Nanotechnology (WIN) thematic research areas.

electric vehicles where lightweight batteries that provide high power density to cover long distance between charges are required. Lithium-ion batteries (LIBs) have become the fastest growing and most promising battery chemistry, easily outperforming nickel–cadmium technology because of their higher energy density. The importance of LIBs in laying the foundation for a wireless, potentially fossil-fuel free society cannot be overstated: the 2019 Nobel Prize in Chemistry has been awarded to three pioneers in this field—John B. Goodenough, M. Stan Whittingham, and A. Yoshino—for their research in improving battery technology.

Lithium-ion batteries are desirable because little maintenance is required and they have wide operational temperature ranges, high output voltages, and no memory effects. Despite these advantages, limitations remain, including limited lifecycle (although this is being addressed), structural instability of the cathode material on deep charge, and rigid demand in temperature and humidity control. Hence, there are strong needs for post-LIB technologies for next-generation technology, including lithium–oxygen (Li–O₂) and lithium–sulfur (Li–S).

Li–O₂ batteries that are based on pairing reversible lithium oxidation at the anode and oxygen reduction at the cathode to generate current are expected to deliver the highest energy density possible, although this battery system generally suffers from large overpotentials during charging. These overpotentials are due to side reactions between the discharge products—lithium superoxide (LiO₂) and lithium peroxide (Li₂O₂)—and the aprotic electrolyte, as well with the carbonaceous cathode. In attempts to overcome the interfacial formation of LiCO₃ *via* reaction of Li₂O₂ with carbon, non-carbonaceous cathode materials are being researched. In “The Importance of Nanometric Passivating Films on Cathodes for Li–Air Batteries”, Adams *et al.* determined that the surface layers on

conductive Ti-oxide-based materials are a key factor in the charging mechanism for Li–O₂ batteries.²⁶

Model studies using electrodes prefilled with commercial Li₂O₂ powders revealed that the nature of the surfaces of materials can play critical roles in the oxygen evolution reaction (OER) by either promoting or limiting charge transport. By using a combination of S/TEM, online mass spectrometry, X-ray photoelectron spectroscopy, and electrochemical methods to probe the surface of carbon and conductive Ti-based nanoparticles, the researchers determined that oxygen evolution during charging is strongly dependent on their surface properties. For instance, two TiC nanocrystalline materials with identical bulk properties but different surface passivation can lead to very different charging profiles. Insulating TiO₂ surface layers on one of the TiC and TiN materials—even as thin as 3 nm—can completely inhibit the charge reaction. This finding demonstrates that facile electron transfer from the catalyst through a nanometric surface layer and into the bulk of a conductive component in a Li–air cathode is the key to efficiency in Li–O₂ chemistry (Figure 3).

Lithium–sulfur batteries are also promising because of their high theoretical energy density, in addition to the natural abundance, low cost, and innocuity of sulfur as an active material. Although Li–S batteries are expected to provide specific energy that surpasses that of LIBs, there are several key problems associated with Li–S battery commercialization, including low sulfur utilization and poor cycle life. These problems are aggravated with high-sulfur-loading cells that attempt to reach practical energy densities. These complications arise mainly from the low electronic conductivity of insulating sulfur and its discharge product, lithium sulfide (Li₂S), as well as the large volume change and lithium polysulfide shuttle during cycling.

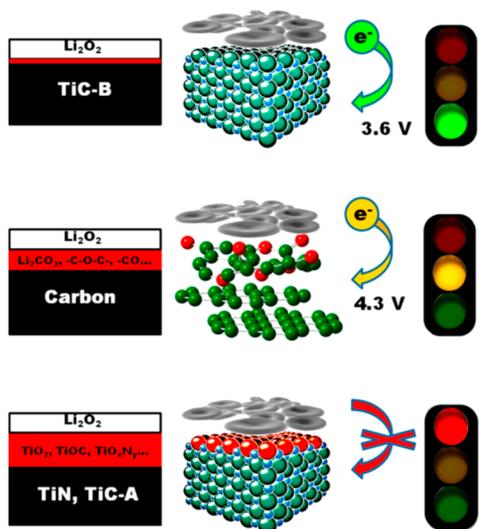


Figure 3. Effects of cathode materials' surface on Li_2O_2 oxidation in $\text{Li}-\text{O}_2$ chemistry is demonstrated. A thin nanometric insulating layer in a $\text{Li}-\text{O}_2$ cathode that changes the facile electron transfer from the solid Li_2O_2 into the bulk is the key to efficient oxygen evolution reactions in $\text{Li}-\text{O}_2$ chemistry. Reprinted from ref 26. Copyright 2014 American Chemical Society.

To understand the problem of controlling the sulfur fraction in porous carbon hollow spheres and to determine how porosity can affect the electrochemical performance of the $\text{Li}-\text{S}$ cells fabricated with these host materials, the Nazar group performed work that led to the publication "Tailoring Porosity in Carbon Nanospheres for $\text{Li}-\text{S}$ Battery Cathodes" in 2013.²⁷ This study investigated the possibilities of utilizing porous hollow carbon nanospheres as host materials for $\text{Li}-\text{S}$ batteries. A scalable approach to tailor the porosity of the shells of the hollow nanospheres was developed using a pore-former surfactant polydiallyldimethylammonium chloride (polyDADMAC), resulting in optimized carbon spheres that can easily be infiltrated with the active material. Sulfur was mainly confined in 4–5 nm mesopores in the carbon shell and inner lining of the shells, which is beneficial for enhancing charge transfer and accommodating volume expansion of sulfur during redox cycling. This resulted in $\text{Li}-\text{S}$ cells with superior electrochemical performance at a high 1C rate and capacity retention of 90% over 100 cycles. By deliberately creating shell porosity and utilizing the interior void volume of the carbon spheres,

sufficient space for sulfur storage was generated and the electrolyte pathway was improved (Figure 4).

Another approach to address low S utilization and short cycling life due to LiPS shuttling in $\text{Li}-\text{S}$ batteries was reported by Pang *et al.* in "Long-Life and High-Areal-Capacity $\text{Li}-\text{S}$ Batteries Enabled by a Light-Weight Polar Host with Intrinsic Polysulfide Adsorption".²⁸ Here, a lightweight nanoporous graphitic carbon nitride (high-surface-area $\text{g}-\text{C}_3\text{N}_4$) enabled a sulfur electrode with an ultralow long-term capacity fade rate of 0.04% per cycle over 1500 cycles at a practical C/2 rate. Specifically, it exhibited good high-sulfur-loading areal capacity (up to 3.5 mAh cm^{-2}) with stable cell performance. The strong chemical interaction of $\text{g}-\text{C}_3\text{N}_4$ with polysulfides was demonstrated using a combination of spectroscopic experimental studies and first-principles calculations. The high concentration (53.3 atom %) of accessible pyridinic nitrogen polysulfide adsorption sites was shown to be key for the greatly improved cycling performance compared to that of N-doped carbons. The lightweight sulfur host with a high fraction of LiPS chemisorption sites is well-suited for $\text{Li}-\text{S}$ batteries with long-life and high loading capacity (Figure 5).

As mentioned above, the primary issue with $\text{Li}-\text{S}$ batteries is the polysulfide shuttle effect owing to dissolution of intermediate polysulfide species, which causes active material loss and, hence, loss of the lifetime of the battery. Developments of host materials to curtail this dissolution via physical confinement or chemical binding have been proven to be effective, although the high cost and complicated fabrication present an impediment to their practical applications. In 2016, the Nazar group published "In Situ Reactive Assembly of Scalable Core-Shell Sulfur- MnO_2 Composite Cathodes", in which they demonstrated a simple methodology to fabricate an effective nanometric MnO_2 shell on sulfur particles to encapsulate the polysulfides.²⁹ The *in situ* redox reaction between sulfur and KMnO_4 under ambient conditions produced a bifunctional MnO_2 shell, which acted as a semiconductor to transfer electrons to the sulfur core. As sulfur particles were completely enclosed in the MnO_2 shell, the physical confinement of active material afforded by the MnO_2 core-shell structure and the intrinsic polysulfide binding by MnO_2 led to excellent polysulfide confinement and substantially improved the cycling stability of the $\text{Li}-\text{S}$ battery. Moreover, the authors employed solvent extraction to remove some of the sulfur core to reserve space to accommodate volumetric expansion from sulfur to Li_2S upon discharge. Thus, MnO_2 sheets crystallized

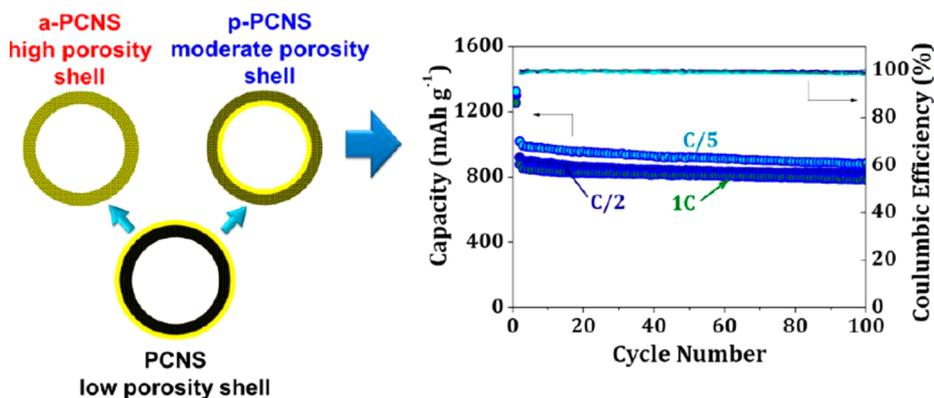


Figure 4. Hollow, porous carbon nanospheres (PCNs) with tailored pore structures as conducting frameworks for lithium-sulfur battery cathode materials. Reprinted from ref 27. Copyright 2013 American Chemical Society.

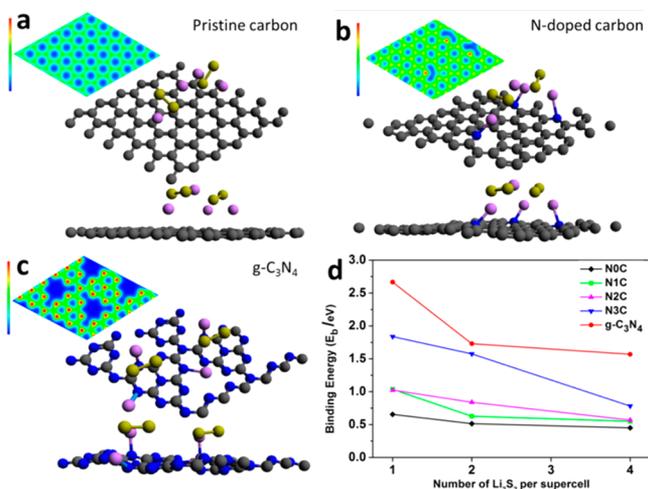


Figure 5. First-principles calculations of the most stable binding configurations after full relaxation of Li_2S_2 molecules. (a) pristine carbon, (b) N-doped carbon (3 N atoms, N_3C), (c) $\text{g-C}_3\text{N}_4$ substrates (bottom panels for side views); insets on top left are the two-dimensional deformation charge distributions of the corresponding substrates without Li_2S_2 (red for accepting electrons, blue for donating electrons). Gray, blue, purple, and yellow balls represent C, N, Li, and S atoms, respectively. (d) Variations of the binding energy of Li_2S_2 molecules binding to the respective substrates, with respect to the number of Li_2S_2 , as calculated by Bader charge analysis. Reprinted from ref 28. Copyright 2016 American Chemical Society.

onto nanosized sulfur particles resulted in cathodes with a very low fading rate of 0.039% per cycle over 1700 cycles in Li–S cells. In addition, directly crystallizing nanometric shells of MnO_2 on micrometer-sized sublimed sulfur delivered stable Li–S cycling performance over 800 cycles (Figure 6). As both sulfur and KMnO_4 are inexpensive and widely used, this production method for MnO_2 -coated sulfur composites can be easily scaled-up for practical applications of Li–S batteries using a very simple reaction process.

Multishelled, hollow structured transition metal oxides (TMOs) have also been investigated for their compatibility with Li-ion batteries. Multishelled TMOs exhibit great potential

for high-energy-density energy storage due to their high packing density, reduced aggregation of nanosized subunits, and excellent capacity and cyclic stability. The 2017 publication by Zhongwei Chen and colleagues, “Tuning Shell Numbers of Transition Metal Oxide Hollow Microspheres toward Durable and Superior Lithium Storage” describes a straightforward synthetic technique to fabricate multishelled porous hollow microspheres made of nanosized primary TMO particles.³⁰ The authors used metal acetate polysaccharide microspheres as a precursor, which could then be applied to fabricate TMO hollow microspheres with tunable shell numbers and compositions to realize its excellent electrochemical performance.

The hierarchical porous quadruple-shelled hollow microspheres with nano Ni–Co–Mn oxide demonstrated more active sites, boosted rate capability, and enhanced volumetric energy density, and showed great tolerance toward volume expansion upon cycling, thus exhibiting excellent Li^+ storage capability with high specific capacity (1470 mAh g^{-1} at 0.2 A g^{-1} and $1073.6 \text{ mAh g}^{-1}$ at 5.0 A g^{-1}) and excellent cycle stability (1097 mAh g^{-1} after 250 cycles at 0.2 A g^{-1}) among TMO anode materials for lithium-ion batteries (Figure 7).

Moving forward into the next decade, WIN will continue to drive key initiatives in nanotechnology research and development for sustainable, important, and impactful results. The Waterloo Institute for Nanotechnology is positioned to capitalize on the next waves of technological development and meeting the energy demands of *Industry 4.0* and *Society 5.0* in the 21st century.

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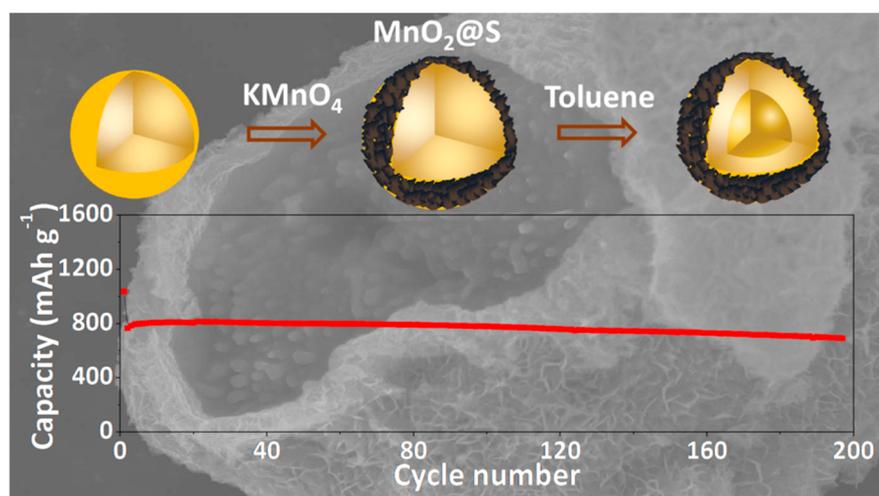


Figure 6. Nanometric MnO_2 shell for sulfur particles: *in situ* redox reaction between sulfur and KMnO_4 produces a bifunctional MnO_2 shell for physical confinement and chemical interaction with polysulfide intermediates. Reprinted from ref 29. Copyright 2016 American Chemical Society.

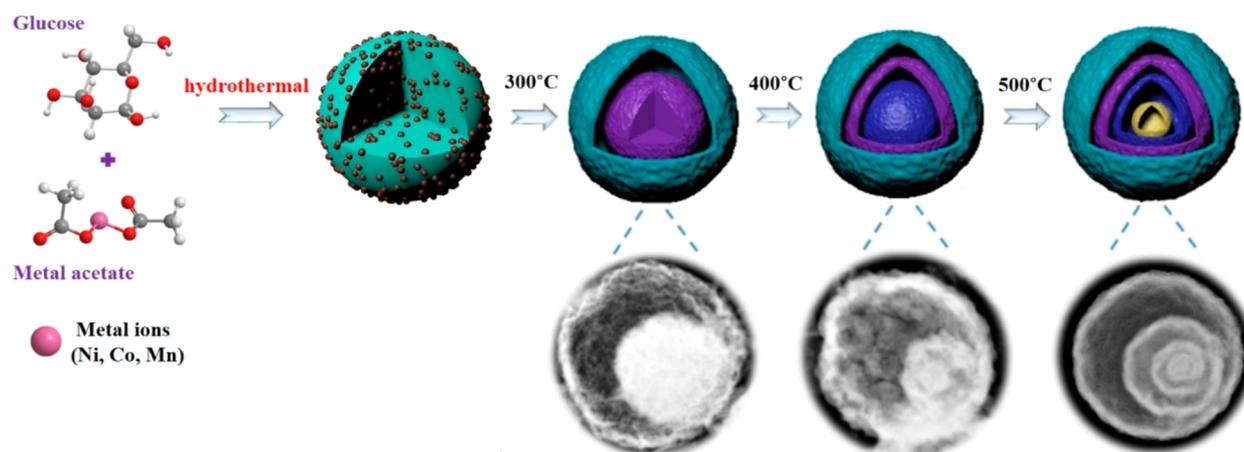


Figure 7. Formation process of transition metal oxide quadrupole-shelled hollow spheres. Reprinted from ref 30. Copyright 2017 American Chemical Society.

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Notes

Views expressed in this editorial are those of the authors and not necessarily the views of the ACS.

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REFERENCES

- (1) Zhang, J.; Con, C.; Cui, B. Electron Beam Lithography on Irregular Surfaces Using an Evaporated Resist. *ACS Nano* **2014**, *8*, 3483–3489.
- (2) Sohn, Y.; Pradhan, D.; Leung, K. T. Electrochemical Pd Nanodeposits on a Au Nanoisland Template Supported on Si(100): Formation of Pd-Au Alloy and Interfacial Electronic Structures. *ACS Nano* **2010**, *4*, 5111–5120.
- (3) Radi, A.; Pradhan, D.; Sohn, Y.; Leung, K. T. Nanoscale Shape and Size Control of Cubic, Cuboctahedral, and Octahedral Cu-Cu₂O Core-Shell Nanoparticles on Si(100) by One-Step, Templateless, Capping-Agent-Free Electrodeposition. *ACS Nano* **2010**, *4*, 1553–1560.
- (4) Hegde, M.; Farvid, S. S.; Hosein, I. D.; Radovanovic, P. V. Tuning Manganese Dopant Spin Interactions in Single GaN Nanowires at Room Temperature. *ACS Nano* **2011**, *5*, 6365–6373.

- (5) Yin, P.; Hegde, M.; Tan, Y.; Chen, S.; Garnet, N.; Radovanovic, P. V. Controlling the Mechanism of Excitonic Splitting in In₂O₃ Nanocrystals by Carrier Delocalization. *ACS Nano* **2018**, *12*, 11211–11218.

- (6) Zhang, X.-Y.; Hu, A.; Zhang, T.; Lei, W.; Xue, X.-J.; Zhou, Y.; Duley, W. W. Self-Assembly of Large-Scale and Ultrathin Silver Nanoplate Films with Tunable Plasmon Resonance Properties. *ACS Nano* **2011**, *5*, 9082–9092.

- (7) Dalsin, S. J.; Rions-Maehren, T. G.; Beam, M. D.; Bates, F. S.; Hillmyer, M. A.; Matsen, M. W. Bottlebrush Block Polymers: Quantitative Theory and Experiments. *ACS Nano* **2015**, *9*, 12233–12245.

- (8) Maher, M. J.; Self, J. L.; Stasiak, P.; Blachut, G.; Ellison, C. J.; Matsen, M. W.; Bates, C. M.; Willson, C. G. Structure, Stability, and Reorganization of 0.5 L-0 Topography in Block Copolymer Thin Films. *ACS Nano* **2016**, *10*, 10152–10160.

- (9) Zhou, L.; Xiang, H.-Y.; Shen, S.; Li, Y.-Q.; Chen, J.-D.; Xie, H.-J.; Goldthorpe, I. A.; Chen, L.-S.; Lee, S.-T.; Tang, J.-X. High-Performance Flexible Organic Light-Emitting Diodes Using Embedded Silver Network Transparent Electrodes. *ACS Nano* **2014**, *8*, 12796–12805.

- (10) Baidya, A.; Ganayee, M. A.; Jakka Ravindran, S.; Tam, K. C.; Das, S. K.; Ras, R. H. A.; Pradeep, T. Organic Solvent-Free Fabrication of Durable and Multifunctional Superhydrophobic Paper from Waterborne Fluorinated Cellulose Nanofiber Building Blocks. *ACS Nano* **2017**, *11*, 11091–11099.

- (11) Natarajan, J. V.; Darwitan, A.; Barathi, V. A.; Ang, M.; Htoon, H. M.; Boey, F.; Tam, K. C.; Wong, T. T.; Venkatraman, S. Sustained Drug Release in Nanomedicine: A Long-Acting Nanocarrier-Based Formulation for Glaucoma. *ACS Nano* **2014**, *8*, 419–429.

- (12) Jahed, Z.; Shahsavan, H.; Verma, M. S.; Rogowski, J. L.; Seo, B. B.; Zhao, B.; Tsui, T. Y.; Gu, F. X.; Mofrad, M. R. K. Bacterial Networks on Hydrophobic Micropillars. *ACS Nano* **2017**, *11*, 675–683.

- (13) Kempaiah, R.; Chung, A.; Maheshwari, V. Graphene as Cellular Interface: Electromechanical Coupling with Cells. *ACS Nano* **2011**, *5*, 6025–6031.

- (14) Dave, N.; Liu, J. Programmable Assembly of DNA-Functionalized Liposomes by DNA. *ACS Nano* **2011**, *5*, 1304–1312.

- (15) Meng, Y.; Liu, P.; Zhou, W.; Ding, J.; Liu, J. Bioorthogonal DNA Adsorption on Polydopamine Nanoparticles Mediated by Metal Coordination for Highly Robust Sensing in Serum and Living Cells. *ACS Nano* **2018**, *12*, 9070–9080.

- (16) Shin, S. R.; Bae, H.; Cha, J. M.; Mun, J. Y.; Chen, Y.-C.; Tekin, H.; Shin, H.; Farshchi, S.; Dokmeci, M. R.; Tang, S.; Khademhosseini, A. Carbon Nanotube Reinforced Hybrid Microgels as Scaffold Materials for Cell Encapsulation. *ACS Nano* **2012**, *6*, 362–372.

- (17) Goldman, A.; Kulkarni, A.; Kohandel, M.; Pandey, P.; Rao, P.; Natarajan, S. K.; Sabbiseti, V.; Sengupta, S. Rationally Designed 2-in-1

Nanoparticles Can Overcome Adaptive Resistance in Cancer. *ACS Nano* **2016**, *10*, 5823–5834.

(18) She, Z.; Ghosh, D.; Pope, M. A. Decorating Graphene Oxide with Ionic Liquid Nanodroplets: An Approach Leading to Energy-Dense, High-Voltage Supercapacitors. *ACS Nano* **2017**, *11*, 10077–10087.

(19) Zarrin, H.; Fu, J.; Jiang, G.; Yoo, S.; Lenos, J.; Fowler, M.; Chen, Z. Quaternized Graphene Oxide Nanocomposites as Fast Hydroxide Conductors. *ACS Nano* **2015**, *9*, 2028–2037.

(20) Thomas, J. P.; Rahman, Md. A.; Srivastava, S.; Kang, J.-S.; McGillivray, D.; Abd-Ellah, M.; Heinig, N. F.; Leung, K. T. Highly Conducting Hybrid Silver-Nanowire-Embedded Poly(3,4-ethylenedioxythiophene):Poly(styrenesulfonate) for High-Efficiency Planar Silicon/Organic Heterojunction Solar Cells. *ACS Nano* **2018**, *12*, 9495–9503.

(21) Armstrong, C. L.; Price, M. B.; Munoz-Rojas, D.; Davis, N. J. K. L.; Abdi-Jalebi, M.; Friend, R. H.; Greenham, N. C.; MacManus-Driscoll, J. L.; Boehm, M. L.; Musselman, K. P. Influence of an Inorganic Inter layer on Exciton Separation in Hybrid Solar Cells. *ACS Nano* **2015**, *9*, 11863–11871.

(22) Srivastava, S.; Thomas, J. P.; Rahman, Md. A.; Abd-Ellah, M.; Mohapatra, M.; Pradhan, D.; Heinig, N. F.; Leung, K. T. Size-Selected TiO₂ Nanocluster Catalysts for Efficient Photoelectrochemical Water Splitting. *ACS Nano* **2014**, *8*, 11891–11898.

(23) Zhang, Z.; Deng, Y.-P.; Xing, Z.; Luo, D.; Sy, S.; Cano, Z. P.; Liu, G.; Jiang, Y.; Chen, Z. Ship in a Bottle Design of Highly Efficient Bifunctional Electrocatalysts for Long-Lasting Rechargeable Zn-Air Batteries. *ACS Nano* **2019**, *13*, 7062–7072.

(24) Mazloumi, M.; Shadmehr, S.; Rangom, Y.; Nazar, L. F.; Tang, X. Fabrication of Three-Dimensional Carbon Nanotube and Metal Oxide Hybrid Mesoporous Architectures. *ACS Nano* **2013**, *7*, 4281–4288.

(25) Rangom, Y.; Tang, X.; Nazar, L. F. Carbon Nanotube-Based Supercapacitors with Excellent ac Line Filtering and Rate Capability via Improved Interfacial Impedance. *ACS Nano* **2015**, *9*, 7248–7255.

(26) Adams, B. D.; Black, R.; Radtke, C.; Williams, Z.; Mehdi, B. L.; Browning, N. D.; Nazar, L. F. The Importance of Nanometric Passivating Films on Cathodes for Li-Air Batteries. *ACS Nano* **2014**, *8*, 12483–12493.

(27) He, G.; Evers, S.; Liang, X.; Cuisinier, M.; Garsuch, A.; Nazar, L. F. Tailoring Porosity in Carbon Nanospheres for Lithium-Sulfur Battery Cathodes. *ACS Nano* **2013**, *7*, 10920–10930.

(28) Pang, Q.; Nazar, L. F. Long-Life and High-Areal-Capacity Li S Batteries Enabled by a Light-Weight Polar Host with Intrinsic Polysulfide Adsorption. *ACS Nano* **2016**, *10*, 4111–4118.

(29) Liang, X.; Nazar, L. F. *In Situ* Reactive Assembly of Scalable Core-Shell Sulfur-MnO₂ Composite Cathodes. *ACS Nano* **2016**, *10*, 4192–4198.

(30) Luo, D.; Deng, Y.-P.; Wang, X.; Li, G.; Wu, J.; Fu, J.; Lei, W.; Liang, R.; Liu, Y.; Ding, Y.; Yu, A.; Chen, Z. Tuning Shell Numbers of Transition Metal Oxide Hollow Microspheres toward Durable and Superior Lithium Storage. *ACS Nano* **2017**, *11*, 11521–11530.